Final Report

Matagorda Bay Inflow Criteria (Colorado River)

Matagorda Bay Health Evaluation

Prepared for

Lower Colorado River Authority

and San Antonio Water System

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LCRA - SAWS
Water Project

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Acronyms and Abbreviations

2YS	Two-Year Average Salinity
2YSPT`	Two-Year Spring Temperature
2YWT	Two-Year Winter Temperature
3MRAT	Three-Month Rolling Average Temperature
CI	Condition Indices
CBOD	Carbonaceous Biochemical Oxygen Demand
COLMB	Colorado River to Matagorda Bay
CV	Coefficient of Variation
DCI	Dermo Condition Index
DI	Dermo Weighted Incidence
DO	Dissolved Oxygen
EAMB	Eastern Arm of Matagorda Bay
ELMR	Estuarine Living Marine Resources
EMB	East Matagorda Bay
FINS	Freshwater Inflow Needs Study
FWS	U.S. Fish and Wildlife Service
GIWW	Gulf Intracoastal Water Way
HCSI	Habitat Composite Suitability Index
HRI	Harte Research Institute for Gulf of Mexico Studies
HSI	Habitat Suitability Index
LCRA	Lower Colorado River Authority
LSWP	LCRA-SAWS Water Project
MAF	Million Acre Feet
MBHE	Matagorda Bay Health Evaluation
MDS	Non-metric multidimensional scaling
MIMP	Mad Island Marsh Preserve
NMFS	National Marine Fisheries Service
NWS	National Weather Service
ODCI	Oyster Dermo Condition Index
OCI	Oyster Condition Index

OP	Orthophosphate
OrgN	Organic Nitrogen
OrgP	Organic Phosphorus
PCA	Principal Component Analysis
POR	Period of Record
RMA	Resource Management Association (modeling software)
RMS	Root Mean Square
SAWS	San Antonio Water System
SC	Suitability Criterion
SHI	Salinity Habitat Interface
SRP	Soluble Reactive Phosphorus
STP	South Texas (Nuclear) Project
SWQM	Surface Water Quality Monitoring
TCEQ	Texas Commission on Environmental Quality
TMATB	Total Matagorda Bay (inflow)
TPWD	Texas Parks and Wildlife Department
TSS	Total Suspended Solids
TWDB	Texas Water Development Board
USACE	United States Army Corps of Engineers
USEPA	United States Environmental Protection Agency
USGS	United States Geological Survey
VSS	Volatile Suspended Solids
WASP	Water Quality Analysis Simulation Program
WAM	Water Availability Model
WMP	Water Management Plan
WUA	Weighted Usable Area

Executive Summary

The Matagorda Bay Health Evaluation (MBHE) team has developed substantial modeling and data analysis, which can be employed to assess the relationship between causative factors and resulting bay condition. Several measures of bay condition have been investigated, including salinity, habitat condition, species abundance, nutrient supply, and benthic condition. This document describes the various means of utilizing the MBHE models and data analyses to establish a suite of Matagorda Bay Inflow Criteria for the Colorado River, which, if achieved in the future, should be protective of bay health and productivity.

It is widely accepted that the Matagorda Bay system, like other Gulf Coast estuaries, is a highly dynamic environment which reacts to many drivers one of which is freshwater inflow. Other factors influencing bay conditions are gulf salinity, meteorology, physiographic modifications, harvest pressures, and large-scale Gulf of Mexico conditions that can affect species productivity in the bay. Any one or more of these factors can be of primary importance in influencing bay conditions at any point in time. Furthermore, there are significant contributors of freshwater inflow to the Matagorda Bay system from sources other than the Colorado River, which contributes approximately 40% of the total inflow into the system on an average basis. Recognizing, however, that the Lower Colorado River Authority (LCRA) – San Antonio Water System (SAWS) Water Project (LSWP) directly impacts the Colorado River flow, and LCRA can only manage Colorado River flow, it remains appropriate to develop a suite of protective Matagorda Bay Inflow Criteria for the Colorado River only.

The principle MBHE work that has been employed to develop the criteria is the salinity, habitat, and benthic modeling for most inflow levels, and the nutrient modeling and data analyses for the long-term flow component. Additional measures of bay health were employed to bolster or confirm the primary model application wherever possible. Also, it was determined that inflow criteria needed to be comprehensive and cover the full flow spectrum from very low flows (near drought-of-record conditions), in which species refuge becomes of primary importance, to higher flow events sufficient to provide adequate nutrient supply to the bay system.

The techniques to develop specific components of the inflow criteria suite focused on appropriate "Design Areas" where MBHE modeling and analysis tools were applied. These areas ranged from the substantial and important Delta area being formed at the mouth of the Colorado diversion channel, which was used to assess very low flow conditions, to the upper half of the Eastern Arm of Matagorda Bay (EAMB) for the inflow regime, and finally, to the entire EAMB for higher flow conditions. Keeping in mind the cautions stated above regarding our sole focus on Colorado River inflow, these Design Areas were deemed to be appropriate. It is important to distinguish between the Design Areas described in this document and monitoring locations which might be established to assess the sufficiency of the recommended Inflow Criteria. The Design Areas are not meant to be synonymous with long-term monitoring areas or somehow exclusively linked to future assessment of inflow criteria. No doubt, long-term monitoring activities will take place within the Design Areas, but will not necessarily be limited to these areas.

The recommended Colorado River inflow criteria are designed to cover the full range of inflow conditions into Matagorda Bay. The inflow suite for the MBHE inflow criteria includes long-term inflow conditions (presented as long-term volume and variability), an inflow regime (presented as MBHE 1-4), and extremely low and infrequent inflow events (termed Threshold). The MBHE freshwater inflow categories and specific criteria as summarized in the table below include a range of inflows with the goal of providing the essential components to maintain the health and productivity of Matagorda Bay.

Inflow Category	Inflow Criteria	Description
LONG-TERM	Long-term Average Volume and Variability	provide adequate bay food supply to maintain the essential food supply and existing primary productivity of the bay system
MBHE INFLOW REGIME	MBHE 4	provide inflow variability and support high levels of primarily productivity, and high quality oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat.
	MBHE 3	provide inflow variability and support quality oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat.
	MBHE 2	provide inflow variability and sustain oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat
	MBHE 1	maintain tolerable oyster reef health, benthic character, and habitat conditions
MINIMUM	Threshold	refuge conditions for all species and habitats

The specific detailed suite of recommended inflow criteria are summarized below:

	Flow Volumes (AF)			Achievement Guideline
Threshold	Maintain 15,000 AF per month			100%

Note 1: Could allow for adaptive inflow management during Threshold conditions. For example, holdback of minimum flow during a given month or months to allow for larger pulse flow release.

Regime	Spring	Fall	Intervening	
MBHE 1	114,000	81,000	105,000	90%*
MBHE 2	168,700	119,900	155,400	75%
MBHE 3	246,200	175,000	226,800	60%

* Based on historical frequency of occurrence

Note 2: For the Threshold and Regime criteria levels (MBHE 1-3), operating protocol ("triggers") are to be established to manage flows by releases from storage so as to satisfy the achievement guidelines recommended above.

MBHE 4	433,200	307,800	399,000	35%**

** MBHE 4 criteria achievement guideline is also based on historical frequency of occurrence. However, it is recommended that Water Availability Model (WAM) results be examined to determine that this frequency is achieved by a combination of years that either 1) fully satisfy all seasonal components of the MBHE 4 criteria, or 2) are projected to have an annual flow that exceeds the volume (approximately 1.6 million acre feet [MAF]) necessary to maintain a monthly average of 15 ppt salinity at the Mad Island reef transect (the outermost transect of the upper Eastern Arm Design Area), meet two of the three seasonal components of MBHE 4, and exceed the MBHE 3 criteria for the remaining seasonal component.

Long-Term Volume and Variability	Average at least 1.4 to 1.5 MAF per year	100%

Recommend that WAM results be examined to determine that the projected long-term annual average flow is maintained at a level of at least 1.4 to 1.5 million AF, with a coefficient of variation (CV) value above 0.8.

Note 3: As the satisfaction of all criteria is based on a 59-year WAM simulation, an important adjunct to the Inflow Criteria is the establishment of a monitoring program, which measures key bay health and productivity indicators and verifies the projected response of the bay to flow levels in the Colorado River. Also, it will be necessary to regularly review the basic assumptions (demand, hydrology, etc.) that are fundamental to the WAM simulation upon which successful criteria achievement is projected. Regular reassessment based on new data and refined assumptions would provide the basis for an adaptive management approach to maintaining bay health and productivity.

1.0 Introduction

House Bill 1629, the enabling legislation for the Lower Colorado River Authority (LCRA) - San Antonio Water System (SAWS) Water Project (LSWP), includes a requirement to "ensure that beneficial inflows remaining after any diversions will be adequate to maintain the ecological health and productivity of the Matagorda Bay system." The LSWP Matagorda Bay Health Evaluation (MBHE) team is charged to establish a method or methods that will: (1) allow an estimate of changes in bay health and productivity due to changes in freshwater inflow and determine if that level of change is acceptable within the LSWP-authorizing legislation; and (2) provide criteria for freshwater inflow to the Surface Water Availability (SWA) Study Team to guide their analysis of project design alternatives and system operating guidelines. This document focuses on the second of these two project objectives.

It is widely accepted that the Matagorda Bay system, like other Gulf Coast estuaries, is a highly dynamic environment, which reacts to many drivers one of which is freshwater inflow. Other factors influencing bay conditions are near-shore gulf salinity, meteorology, physiographic modifications, harvest pressures, adjacent land-use change, habitat alterations or losses, and large-scale Gulf of Mexico conditions. All of these factors can affect habitat and species distributions and productivity in the bay, as well as chemical constituents, the availability of food, fishing pressure, and, for migratory species, the status of the larger population in the Gulf. It is important to realize that little can be done to control many of the factors that influence bay conditions or the abundance of various species. This lack of control is compounded when considering that, at any given time, one or more of these factors other than freshwater inflow can be of *primary* importance in determining the abundance of an organism within the bay. An unknown but considerable source of the scatter in measures of water quality and in the abundance of organisms is due to these non-inflow sources of variation.

Furthermore, even the oversimplification of treating freshwater inflow as the sole determinant of bay health and productivity presents its own complexities. The Colorado River is not the sole source of freshwater inflow to the bay, but rather contributes approximately 40% of the total inflow into the Matagorda Bay system on an average basis, and this contribution varies greatly from year to year. The Lavaca River also flows into Matagorda Bay as well as numerous coastal watersheds, which can contribute substantially to the total bay inflow.

In addition, the timescale of changes in the system, due to all but the most extreme events, is generally long, often measured in years. It is also true that no matter how well developed the measures of bay health and productivity are, the complexities and natural variability of the system make it difficult to monitor induced changes on a real-time basis. Even the long-term monitoring program which is recommended to support the implementation of the inflow criteria will require analysis of results over a lengthy timeframe to extract useful information about trends and changes in bay conditions and their causes.

This difficulty in directly measuring on a real time basis the health and productivity of the bay system leads us to the development and implementation of inflow criteria. Inflow can be monitored on a real time basis and by using the storage capacity of the Highland Lakes, inflows from the Colorado River can be managed to a degree. Inflow criteria can also be comprehensive in addressing flow levels ranging from very high flows, which contribute substantially to the nutrient supplies in the bay, all the way to maintenance of minimum inflows during near-drought-of-record conditions. The criteria presented herein meet the objective of comprehensively addressing the full spectrum of inflow conditions from flood to drought.

Because the proposed criteria embody achievement guidelines, which suggest that certain flow conditions should be maintained or exceeded a certain percentage of the time, it will be necessary to utilize a forecast of future inflow conditions, such as that provided by the WAM model that has been developed for the lower Colorado basin, to determine if the criteria will be satisfied. Operationalizing the proposed criteria will require establishment of an operating protocol for the Colorado River system that, when superimposed on historical hydrology, yields results satisfying the full suite of inflow criteria. The MBHE team also suggests that the operations process could provide an opportunity to adjust the operating protocol when unusual conditions in the coastal inflows (substantially higher or lower than normal) exist. Adopting this type of adaptive management should provide an opportunity to both protect bay health and productivity and meet long-term water supply needs.

Finally, the proposed criteria for bay inflows will require review from time to time, based on the best estimates of inflow conditions that maintain bay health and productivity according to the models, analyses, and future data collection. Projecting achievement of the inflow criteria provides a level of confidence that bay health and productivity will be maintained so long as the operating protocol are followed. Assessment of the results of long-term monitoring data and subsequent updated modeling and analysis will provide the foundation for another level of adaptive management. In this iterative process, inflow criteria can be regularly reviewed and adjusted to respond to the results of additional data collection.

2.0 Matagorda Bay Health Evaluation (MBHE) Measures and Components

The framework adopted by the MBHE team to assess maintenance of bay health and productivity is premised on a broad range of "measures," which characterize various aspects of the bay system specifically:

- salinity;
- habitat;

  plant productivity/biomass;

  oyster reef condition;

  habitat quantity and quality (for five species);
- abundance;

  eight species, four gear types, with some level of spatial and temporal aggregation can be used in combination or different permutations, depending on the strength of statistical relationships;
- bay food supply;

  nutrients affecting chlorophyll-a;

  organic matter from the watershed;
- benthic condition;

  diversity;

  productivity, and

  biomass.

There is significant interdependence between the various measures of bay health that are being addressed by the MBHE studies.

In the process of developing freshwater inflow criteria for the bay, the MBHE team employed, to the extent possible, all five of the selected measures of bay health. Upon preliminary application of the full range of measures, a trophic level (e.g. bottom to top of the food chain - primary productivity, marsh plants, benthos, juvenile shellfish and forage fish, nekton) approach was determined most feasible, with emphasis on habitat, oyster reef and benthic condition analyses during a range of inflow conditions. The MBHE hydrodynamic and salinity models provide a key underpinning for each of these assessments. The abundance work using the Texas Parks and Wildlife Department's (TPWD) Coastal Fisheries database provided guidance on the relationship between certain "indicator" species and inflow and was employed to assess the consistency of the inflow criteria with long-term measured results. Finally, the MBHE nutrient modeling was utilized to further confirm inflow criteria and to provide the basis for criteria focused on maintaining long-term average volume and variability, which is important to maintaining all components of the system including bay food supply.

The focus of the freshwater inflow criteria development at all inflow levels is on a trophic level assessment that evaluates primary productivity, marsh productivity, the health/condition of oyster reefs, the available habitat for juvenile shellfish and forage fish, and the maintenance of benthic conditions in Matagorda Bay. The tools used specifically for the habitat assessment include the MBHE habitat model and oyster suitability criterion model. The development of these tools and detailed descriptions of their use are presented in the Habitat Assessment Final Report (MBHE 2007a). The habitat modeling relies on the hydrodynamic/salinity model developed as part of the project, as reported in the Hydrodynamic/Salinity Modeling Final Report (MBHE 2006b) and supplement (MBHE 2008). Three studies were used to support the assessment of benthic condition in Matagorda Bay including an analysis of long-term benthic community structure data (Montagna 2008, Kinsey 2006), characterization of benthic habitat variability (Montagna et al. 2006a), and benthic productivity modeling (Montagna 2008, Montagna et al. 2006b). The basis for the bio-statistical data analysis and modeling is documented in the 2007 Bio-Statistics Final Report (MBHE 2007b). Finally, the bay food analysis focused on the development of a Water Quality Analysis Simulation Program (WASP) model as described in the Bay Food Supply, Nutrient and Chlorophyll-a Modeling Final Report (MBHE 2007c), which when coupled with the hydrodynamic model, allows projection of bay primary productivity as represented by chlorophyll-*a*. A brief overview of each tool is provided in the sections below, followed by the freshwater inflow criteria development.

2.1 Hydrodynamic and Salinity Models

Estuarine hydrodynamic and salinity transport are essential processes which, in part, control the bay environment and its habitats. Movement of water and the resulting salinity patterns are elemental and drive many of the higher estuarine processes; hence, a hydrodynamic and salinity transport model is essential to assess changes in habitat, nutrient balances, and productivity resulting from altered inflow regimes. After an extensive review of available models, the MBHE team selected the RMA model family (the family of finite element models supported by the U.S. Army Corps of Engineers [USACE]) to perform hydrodynamic/ salinity transport modeling for the LSWP.

The initial step in the development of a hydrodynamic/salinity transport model is the construction of the model domain. Matagorda Bay model development began with a pre-existing model mesh of the bay, including previously collected bathymetric data. Early in the MBHE process, team members realized that the marshes that constitute the fringes of Matagorda and East Matagorda Bays are areas that might be affected by the project and that exhibit the potential for enhancement by small variations in project operation. Because these coastal marsh/wetlands areas are important to the assessment of the bay health, the team extended the model into these areas, which lie on either side of the Colorado River and to the north of the Gulf Intracoastal Water Way (GIWW) from Oyster Lake on the west to Lake Austin on the east. The final model grid is shown in Figure 1.

The team compiled data from a number of sources to construct a new RMA-based model capable of simulating the complex wetting/drying cycle of estuarine fringe marsh/wetlands areas. The new RMA model utilizes a technique known as the "Marsh Porosity Method" to simulate these complex wetting/drying cycles. The Marsh Porosity Method allows the model to transition gradually between wet and dry states. This technique allows the model to dynamically lower the ability of the element to hold water, much like squeezing a sponge. Aside from more accurately depicting reality, the major advantage of this technique is improvement in the calculation of the shoreline boundary position for intermittently flooded wetlands and tidal flats, resulting in a more stable model.

The MBHE team compiled available data to be used in the calibration and validation of the Matagorda Bay hydrodynamic/salinity transport model. After a thorough evaluation of the available data to identify the most appropriate calibration and validation data sets, results from the 2003 intensive survey conducted by the Texas Water Development Board (TWDB) and others were chosen to serve as a calibration data set. A 1993 intensive survey was chosen as a short-term validation period. The model performs well in the short-term calibration to the 2003 survey data and performs acceptably in validation to the less robust 1993 data set. Longer term validation was also performed during 2006 using long-term salinity monitoring data available from several sources. The model also performs well in the long-term validation and is considered calibrated and validated for use as a planning and evaluation tool in the LSWP.

To provide a long-term simulation of bay hydrodynamics and salinity, the required input data was assembled to model the period from July 1995 through December 2003. This span of time included two extended low flow periods of 20 and 22 months, respectively, as well as a 22-month period of high flow. These results provided the underlying hydrodynamics and salinities for the habitat and nutrient modeling.

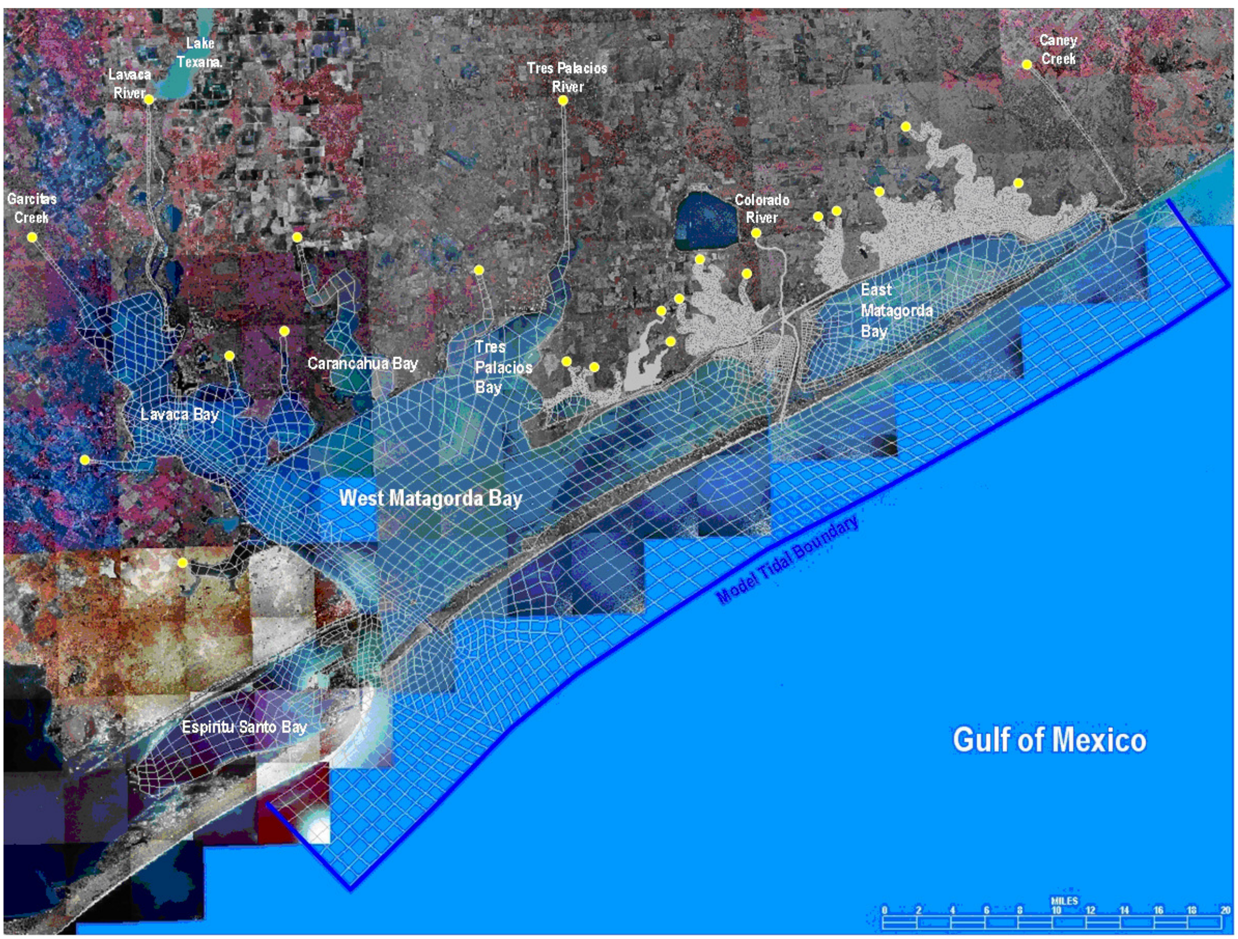


Figure 1. Hydrodynamic/Salinity Model Mesh.

2.2 MBHE Habitat Model

Over the course of the study period, a series of computer programs that comprised the MBHE habitat model were developed to evaluate Matagorda Bay habitat conditions and predict potential changes. As part of model development, programs were integrated to automate habitat modeling, aid in the calculation of weighted usable area (WUA) for each key species, and graphically display the results. The underlying concepts and methodologies employed in the MBHE habitat model are similar to instream flow modeling concepts and methodologies that have been used in rivers and streams over the past several decades (Estevez 2002, Mattson 2002, Annear et al. 2004). Additionally, several recent studies have been conducted that directly apply these concepts to bays and estuaries (Brown et. al 2000; Christensen et. al 1997; Rodgers 2001; Rubec et al. 1999).

Inputs utilized by the habitat model include habitat suitability relationships, high-resolution maps of existing physical habitat, and time-varying salinity model predictions. Given the number of species to be analyzed, the expanse of the area analyzed, differences in spatial resolution and the time-varying nature of the inputs, development of a custom application was necessary to ensure reproducibility of results and to reduce time required for both computer processing and user intervention. As such, the salinity to habitat interface (SHI) was developed to provide a fast tool that could automatically assemble and analyze many different inputs. The development of SHI is documented in MBHE (2007a).

A major input to the habitat model was the habitat suitability indices (physical and chemical) developed for the key species as described in MBHE (2006a, 2007a). As previously described in MBHE 2006a, there are two major biological data sources for the Texas Gulf coast: the TPWD coastal fisheries database and the National Marine Fisheries Service (NMFS) drop trap sampling data. However, the two databases differ in their ability to define organism density relationships as a function of physical habitat. The NMFS drop trap data provides an advantage over the TPWD coastal fisheries database because NMFS drop trap sampling was conducted in many different physical habitat types including coastal marshes (edge and interior), submerged aquatic vegetation, oyster reefs, and shallow non-vegetated bottom. The TPWD gear types are primarily used to sample open bay bottom and are not used within coastal marsh areas. Additionally, TPWD recorded biological sample data (in most instances) and do not include information on vegetation adjacent to TPWD bag seine pulls. Therefore, the NMFS drop trap sample data was used to develop physical habitat suitability criteria for each of the key project species. As limited samples were available from the immediate project area, the project team expanded the data set to include Galveston, Lavaca, and San Antonio bays. The suitability criteria for physical habitat were fitted using normalized frequencies from the combined data set as discussed in MBHE 2006a.

Chemical habitat selection is associated with an organism's affinity to certain salinities or a salinity range. Within the project area, a wealth of salinity and organism data is available from TPWD routine monitoring collections, but that data was collected for purposes other than the development of suitability criteria for juvenile organisms within marsh habitats. Therefore, the TPWD coastal fisheries database was not applicable for exclusive use in suitability curve development. Suitability indices for salinity were developed instead from the literature using a modified envelope approach. Enveloped suitability criteria are often used when site-specific suitability criteria are not available or inherent concerns with bias exist (Jowett et al. 1991, Dunbar and Ibbotson 2001). In the context of the MBHE study, enveloped suitability criteria for salinity were derived by superimposing a composite suitability curve over the majority of literature-based observation data and existing species-specific selection criteria, then reconciling that composite curve with recent studies and physiological results when available.

Initially, salinity ranges tolerated by each of the key species were compiled from National Oceanic and Atmospheric Administration's (NOAA) Estuarine Living Marine Resources (ELMR) Program information (Patillo et al. 1997). The U.S. Fish and Wildlife Service (FWS) series on Species Profiles: Life Histories and Environmental Requirements (Gulf of Mexico) was then reviewed for the same key species (Blue crab [1986], brown shrimp [1983], white shrimp [1984], Atlantic croaker [1983], and Gulf menhaden [1983]). FWS Habitat Suitability Index models are available for four of the key species (Northern Gulf of Mexico brown and white shrimp [1983], juvenile Atlantic croaker [1985], Gulf menhaden [1982]) and were reviewed in detail. Salinity selection was then refined for each of the key project species using data collected from studies conducted by the Fisheries Ecology Branch of the NMFS Galveston Laboratory (see http://galveston.ssp.nmfs.gov/research/fisheryecology/publications/). This collection of studies (referenced in MBHE 2006a as the NMFS dataset) provided substantial information for juvenile organisms collected within shallow non-vegetated bottom and marsh habitats; however, limited samples from the immediate project area were available. Therefore, the NMFS data was again expanded to include Galveston, Lavaca, and San Antonio bays for the salinity suitability development.

The peak density zones for the key species in neighboring bays as described by the TPWD freshwater inflow recommendation studies (Lee et al. 2001, Pulich et al. 1998) were also evaluated for the suitability criteria development. Additionally, many species-specific studies relative to salinity selection have been performed, as well as laboratory studies evaluating salinity effects on survival, growth, and metabolic rates of juveniles. A few examples of laboratory studies evaluated include Chazaro-Olvera and Peterson (2004), "Effects of Salinity of Growth and Molting of Sympatric Callinectes spp. from Camaronera Lagoon, Veracruz, Mexico" from the *Bulletin of Marine Science,*. and Peterson et al. (1999) "Does salinity affect somatic growth in juvenile Atlantic croaker, *Micropogonias undulatus* (Linnaeus)?" Evaluating components of growth and metabolic rate at various salinity levels also provides insight as to the suitability of a prescribed range. Therefore, physiological information was also incorporated into suitability curve development. An extensive list of non-cited references that were reviewed and incorporated in physical and chemical suitability criteria development where applicable are presented in Section 9.0

The habitat model boundary extends across Matagorda and East Matagorda Bays into the marshes at Oyster Lake, Mad Island Marsh Preserve (MIMP), Culver Marsh /TPWD Mad Island Wildlife Management Area, Little Boggy Bayou, and the Big Boggy/Lake Austin marsh complex (Figure 2). Only shallow-water habitats (<2m in depth) that are available to the key project species were evaluated in the habitat model. These physical habitats include estuarine marsh, submerged aquatic vegetation, oyster reef, and shallow non-vegetated bottom. Juveniles for this assessment are described as the life stage of the key species that would most likely be found in these types of habitat. It is acknowledged that an open bay bottom greater than 2m provides habitat for key species life stages (including juvenile shrimp and menhaden). However, as described above, the data used to develop the chemical and physical habitat suitability criteria used in the model were taken from sampling efforts that focused on shallow-water habitats. Therefore, to be consistent with the development of these criteria, areas greater than 2m in depth are not included in the habitat model.

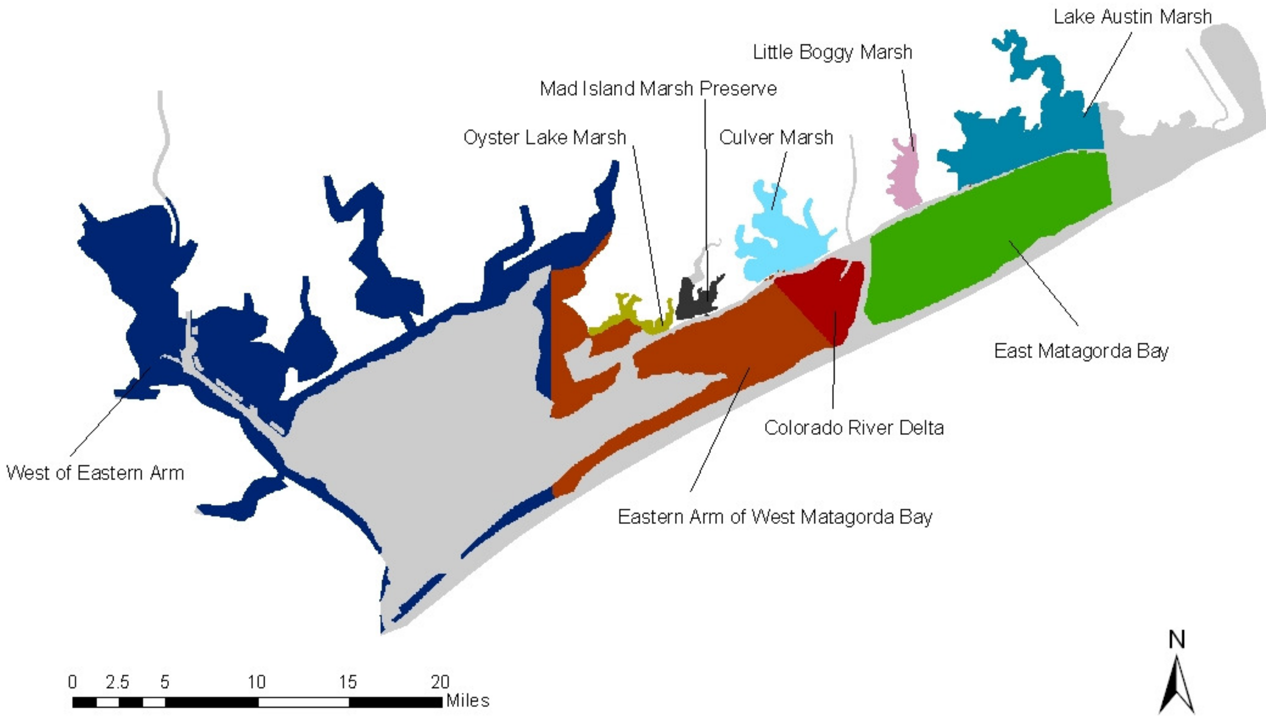


Figure 2. Map of the current extent of the salinity model within the Matagorda Bay system and habitat model segments (denoted by different colors and labels) evaluated during freshwater inflow criteria development.

The main inputs to the habitat model are 1) physical habitat provided by the marsh characterization task (Figure 3), the 2007 oyster reef map of the new Colorado River Delta (Figure 4), and the bathymetric data from the RMA-2 hydrodynamic model, and 2) chemical habitat provided by the RMA-4 salinity model.

The salinity model is comprised of 40,133 points and provides output at each node on a 30-minute time-step. Average salinity applicable to each species was calculated over a time period significant to that species. The time periods and selection methodology for each modeled juvenile species is described in MBHE 2006a, and summarized as follows: blue crab (February to June), brown shrimp (April to July), white shrimp (July to November), Atlantic croaker (January to June), Gulf menhaden (April to August), and annually for low and high estuarine marsh. Juvenile brown shrimp, for example, are most abundant in Matagorda Bay between April and July; therefore, habitat suitability was determined for brown shrimp using salinity output from that period. After salinity model output has been averaged for a particular time period, it is plotted in a geographic information system (GIS) and serves as the chemical habitat input for the analysis of that particular organism. A one-year period was used to determine average salinity for all marsh habitats. The physical habitat input remains the same for all analyses.

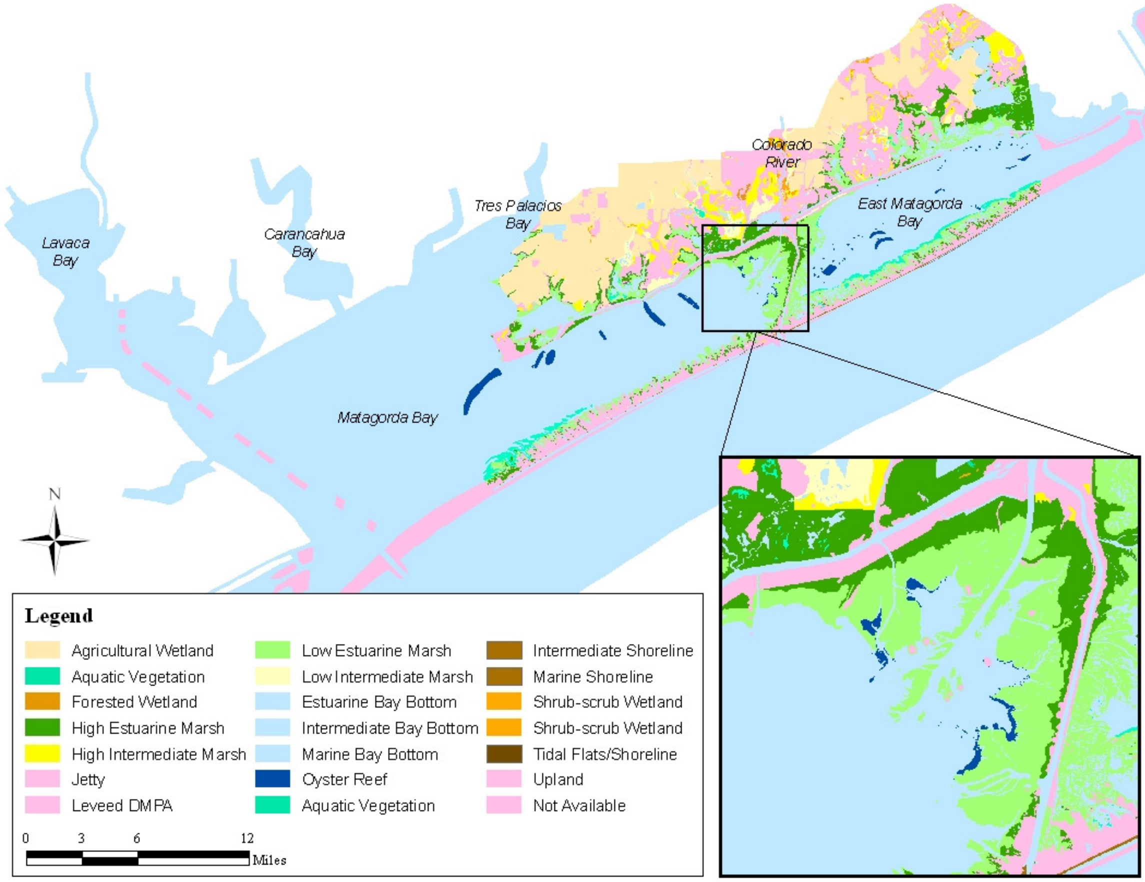


Figure 3. Map of physical habitats within the project area extending from Tres Palacios Bay to Lake Austin, including East Matagorda Bay.

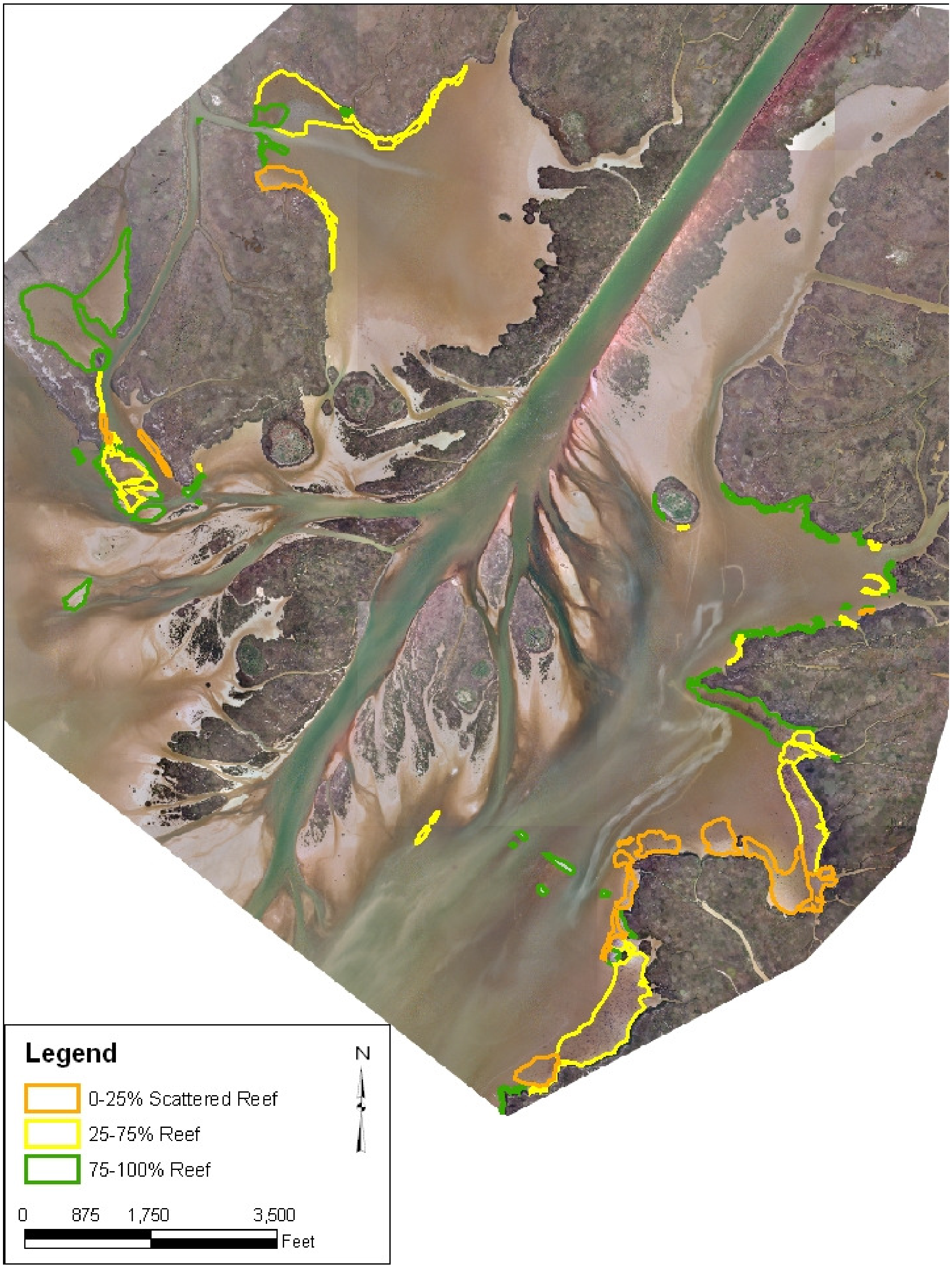


Figure 4. Map of oyster reefs in the new Colorado River Delta on March 2007 aerial photograph.

Within GIS, the area encompassed by the habitat model was divided into square 10 m grid cells for both the physical habitat and chemical habitat inputs. The Habitat Suitability Index (HSI) value corresponding with each physical habitat and chemical habitat type for a particular juvenile organism was assigned to the cells within both of the input files. Both physical habitat HSI and chemical habitat HSI values range from 0 to 1. A selection value of 1 is the highest value assigned and indicates juvenile organisms of that species are found in the highest abundance within that habitat. Lower selection values are assigned to other habitats with proportionally lower populations of juveniles. Any habitat that is not suitable for a juvenile species receives a ranking of 0 and is consequently designated as an area that is not available for the organism. The two habitat inputs are overlaid in GIS so that every grid cell has a corresponding physical habitat attribute and chemical habitat attribute. These two habitat input files are created individually for each of five key species: brown shrimp, white shrimp, blue crab, Gulf menhaden and Atlantic croaker. The overall suitability of each grid cell is evaluated by calculating a habitat composite suitability index (HCSI) represented by the equation:

$$HCSI = PSa(CSa)$$

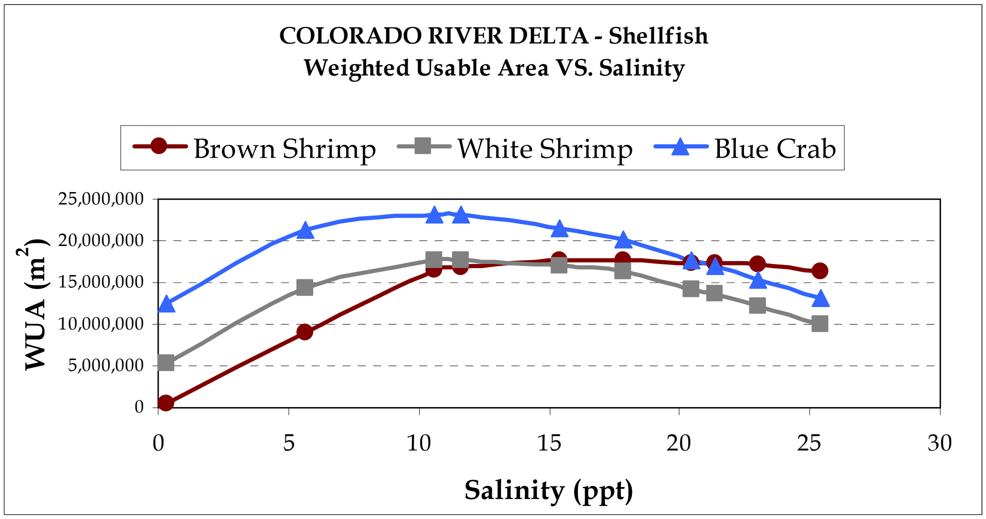
where:

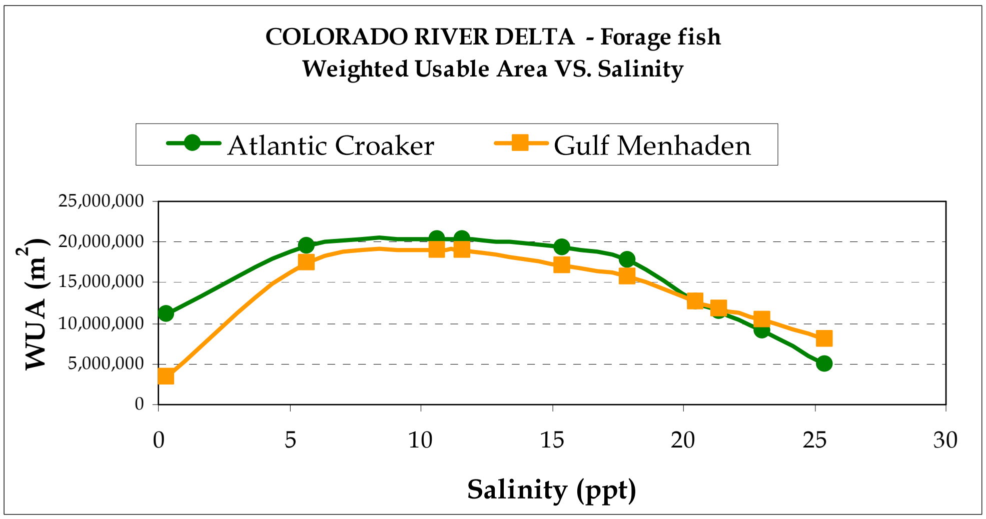
HCSI = the product of the physical HSI (PS) for an organism (a), and chemical HSI (CS) of each grid cell.

Additionally, relative productivity (representing a proportion of maximum productivity), of low and high estuarine marsh habitats within the physical habitat input file, was evaluated based on each salinity input file. The marsh productivity relationships with salinity are presented in MBHE 2006a.

2.2.1 Habitat Model Results

For the freshwater inflow criteria development, the project team conducted extensive model runs to evaluate the amount of weighted usable area (WUA) for each juvenile organism and low and high estuarine marsh versus a range of freshwater inflow scenarios represented by a change in salinity regime. The monthly average salinity at a model node located near the center of each segment was assessed, and the range of monthly salinity conditions at that location from 1995-2002 was determined. The analysis was conducted over that particular range of salinities, at approximately 5 ppt increments. The SHI tool was used to convert the spatial salinity model output across each model segment to GIS format for each month corresponding with the 5 ppt intervals being evaluated. In effect, a salinity contour map was created with the average monthly salinity at a representative node being the salinity for the analysis. The WUA for each organism was calculated by first multiplying each HCSI value by cell area. The results were then summed across the model area of interest (e.g. Colorado River Delta, MIMP, Eastern Arm of Matagorda Bay (EAMB), etc.). The WUA for estuarine marsh was calculated for each individual marsh type by first multiplying the relative plant productivity by cell area. Again, the resulting values were summed for an overall WUA value relative to the model area of interest. The WUA versus salinity relationships were plotted graphically for three trophic levels (which encompass the key species and marsh; shellfish, forage fish, and estuarine marsh) within each of the model segments. Examples of the WUA to salinity relationships developed from the Colorado River Delta, MIMP, and the EAMB are presented in Figures 5, 6, and 7, respectively. These relationships were used in development of freshwater inflow criteria.





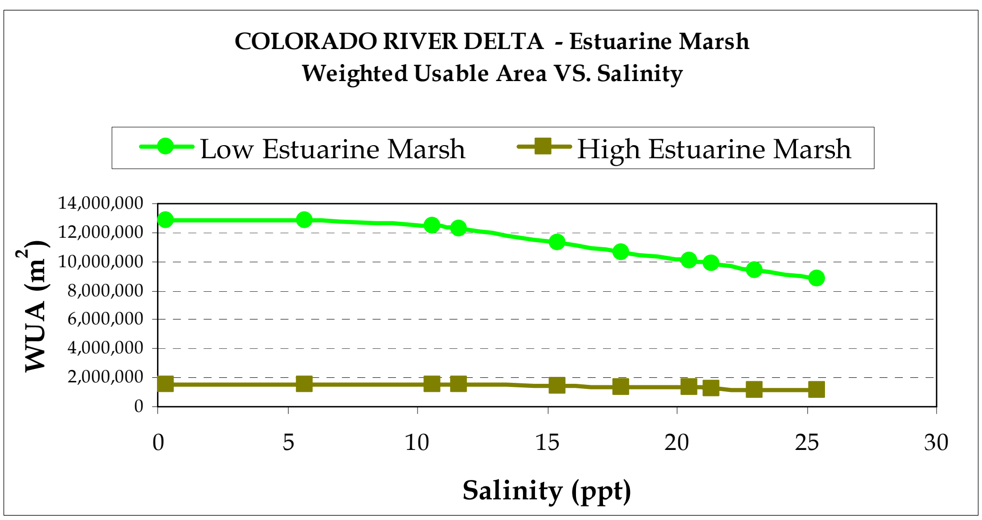
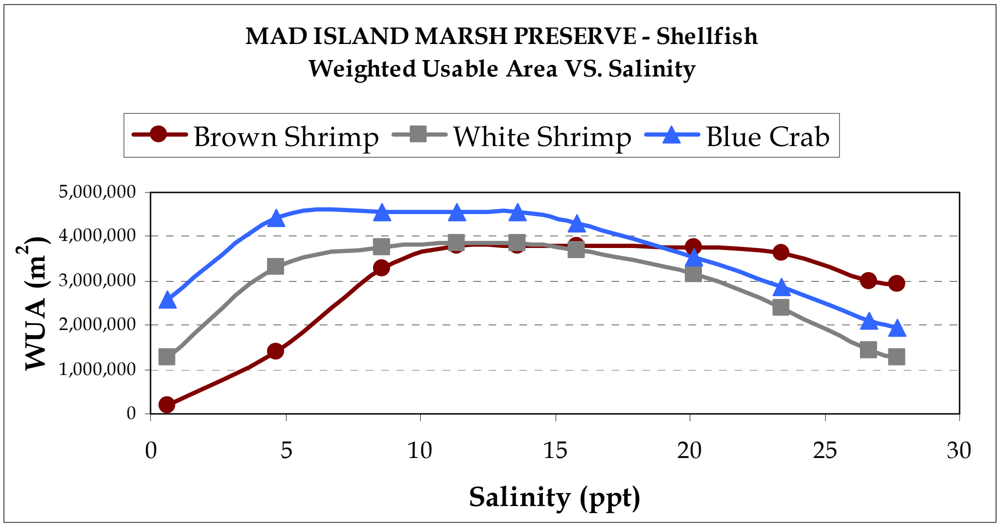
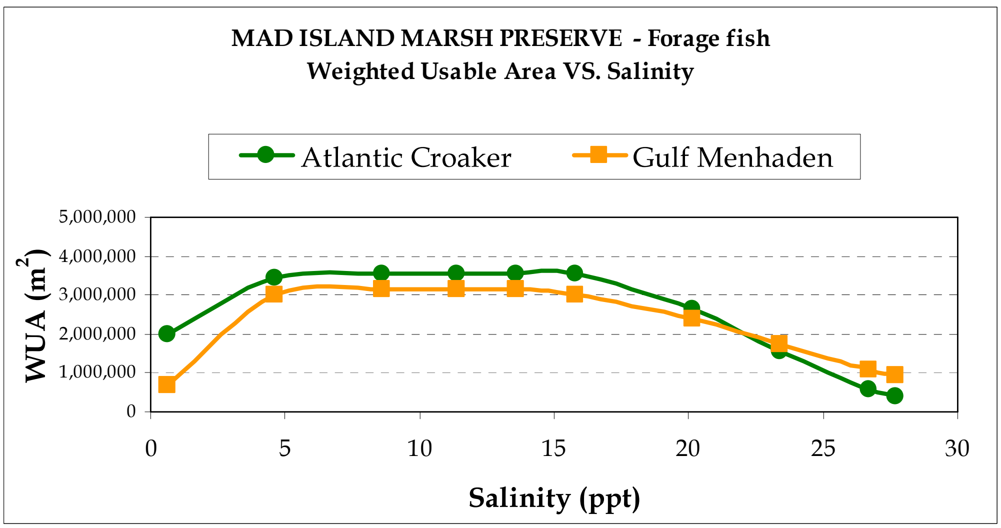


Figure 5. Weighted usable area to salinity relationships for individual trophic levels in the new Colorado River Delta.





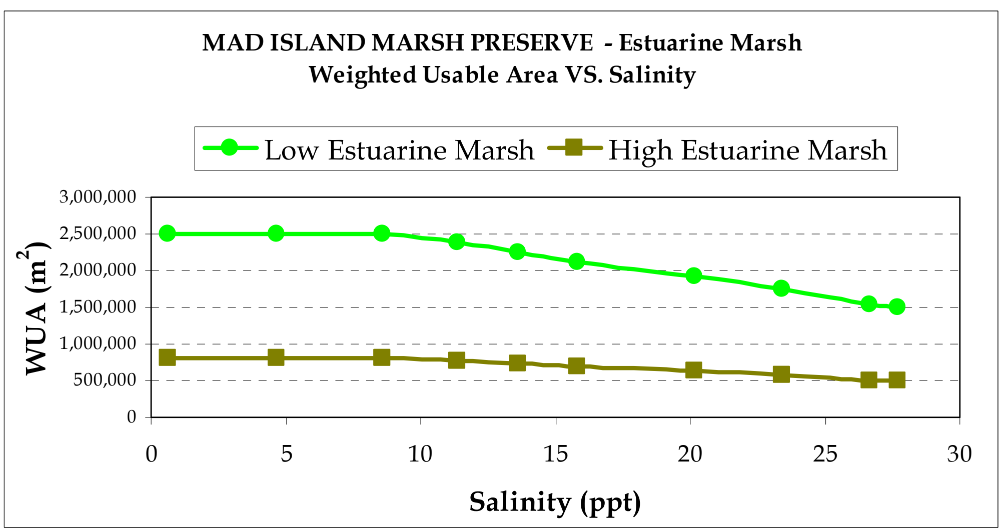
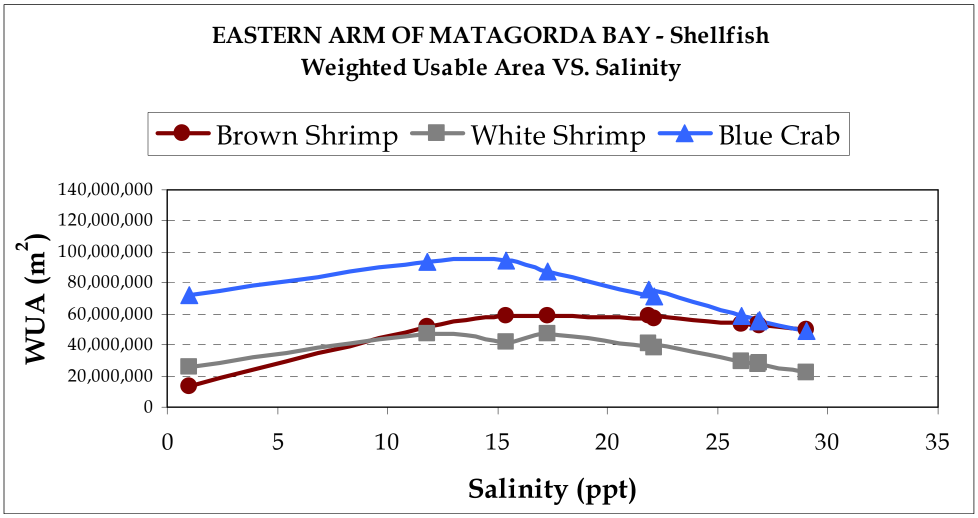
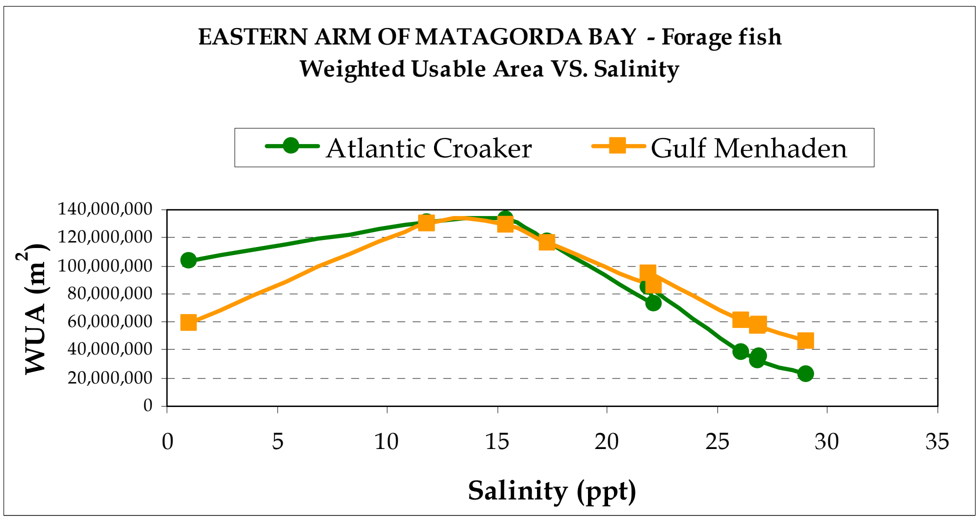


Figure 6. Weighted usable area to salinity relationships for individual trophic levels in the Mad Island Marsh Preserve (MIMP).





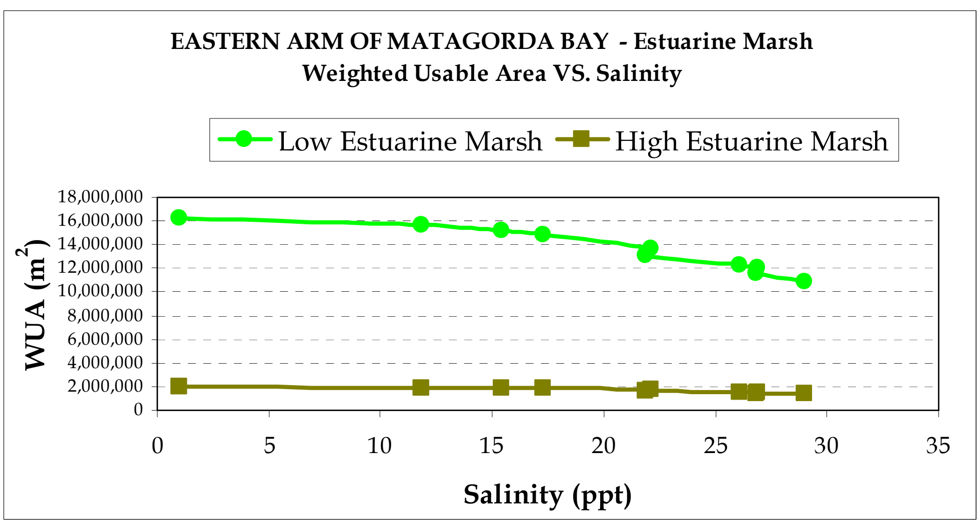


Figure 7. Weighted usable area to salinity relationships for individual trophic levels in the EAMB based on average salinity conditions at Mad Island Oyster Reef.

Model results for the Delta (Figure 5), MIMP (Figure 6), and EAMB (Figure 7) were subsequently selected for the development of inflow criteria, as they are representative of the areas most likely to be impacted by Colorado basin inflows and encompass a wider range of salinity conditions and physical habitats than what is available in the Delta alone. Figure 2 shows the spatial extent of each area; results for EAMB are exclusive of results for the Delta area. The WUA's calculated for marsh productivity and each species for the Delta, MIMP and EAMB were normalized to the greatest amount of WUA predicted for any physical habitat and salinity combination. Habitat quality was then ranked by percentage of maximum WUA for each individual organism as follows:

90-100%	Selected
75-90%	Good
50-75%	Fair
25-50%	Poor
<25%	Refuge

The 90-100% category "Selected" represents the best habitat conditions (e.g., preferred or optimal). The other four categories, "Good," "Fair," "Poor," and "Refuge" are descriptive of their respective habitat conditions. Unlike the Colorado River Aquatic Habitat study (BIO-WEST 2008) that used non-parametric tolerance limits as the method for establishing similar ranges, the MBHE habitat model analysis results do not lend themselves to statistical interpretation; thus, professional judgment was used to assign these categories. Although the physical habitat amount and distribution plays a major role in the calculation of WUA for each organism, it does not change over the modeling period. Attempts were made to include a habitat switching component in this analysis to adjust for changes in physical habitat, but it was determined via interactions with TPWD that the amount of information currently available is too limited to incorporate this aspect. Continued monitoring of physical habitat within the project area would be necessary to account for these changes.

For this assessment, habitat quality rankings associated with WUA calculated from the Delta, MIMP, and EAMB reflecting existing physical habitat conditions and modeled salinities are presented in Table 1 relative to salinity ranges. Table 1 was generated based on habitat model output as depicted in Figures 5-7. For example, on Figure 5, the greatest amount of WUA for white shrimp in the Colorado River Delta was 17,654,000 m^2 at 11.6 ppt salinity. Thus, this value received a 100% ranking and was considered "Selected." At 23 ppt, the WUA for white shrimp was 12,191,000 m^2 (Figure 5) or approximately 69% of the maximum. This corresponds to the "Fair" ranking. To further describe, each percentage of the maximum value per model output (per species per area) was plotted versus salinity as shown in Figure 8 below for white shrimp.

Table 1. Habitat quality rank for each MBHE trophic level.

TROPHIC LEVEL	HABITAT QUALITY RANK*				
	Selected 90-100% WUA	Good 75-90% WUA	Fair 50-75% WUA	Poor 25-50% WUA	Refuge <25% WUA
	Salinity range (ppt)				
Shellfish					
White Shrimp	8-15	15-20	20-25	25-30	> 30
Blue Crab	5-15	15-20	20-25	25-30	> 30
Brown Shrimp	10-25	7-10, 25-30	30-32	32-35	>35
Forage fish					
Gulf Menhaden	5-15	15-20	20-23	23-28	> 28
Atlantic croaker	5-15	15-20	20-23	23-26	> 26
Low Estuarine Marsh	0-15	15-20	20-25	25-30	>30

* Weighted usuable area (WUA) calculated for each species includes selection for physical habitat and salinity.

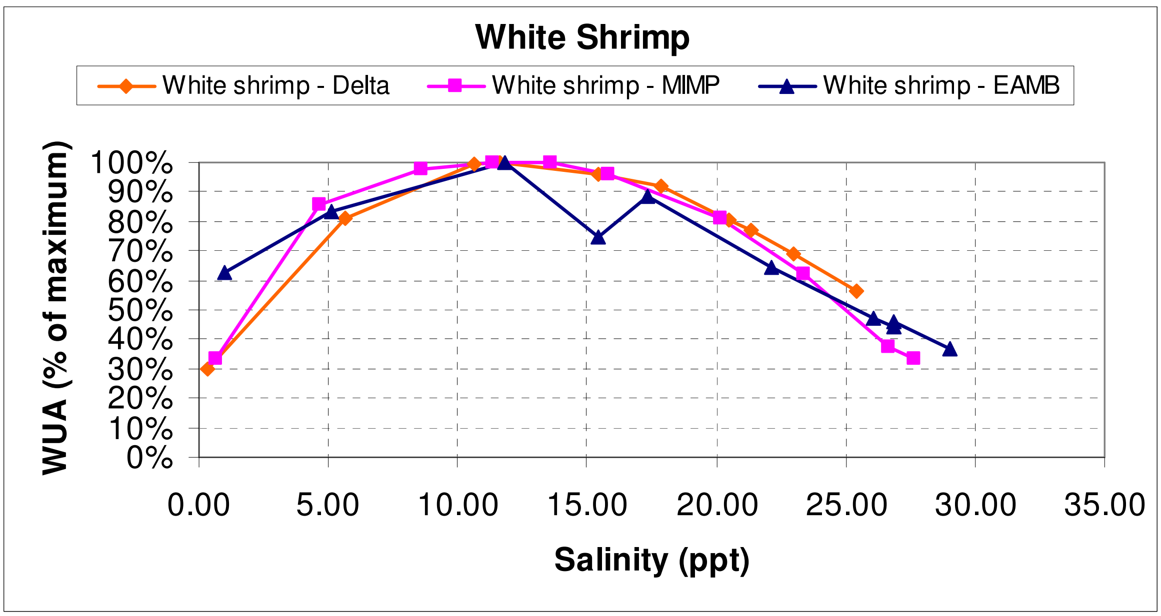


Figure 8. Habitat Model output – Percentage of Maximum WUA for white shrimp in the Colorado River Delta, MIMP, and EAMB.

As shown in Figure 8, the trends from each area are similar but do differ based on physical habitat differences and differing salinity gradients. Additionally, average salinities during the model period did go higher at MIMP and EAMB. Figures 9 through 13 show how the salinity values presented in Table 1 were generated for each key species. Refuge conditions for several key species are extrapolated, since the simulation did not include any periods where average salinity (at a model node near the center of each segment) was greater than 30 ppt in any of the areas. The extrapolation is based upon the chemical suitability function for each species (MBHE 2007a), which shows various levels of decreasing trends in suitability for salinity above 25 ppt.

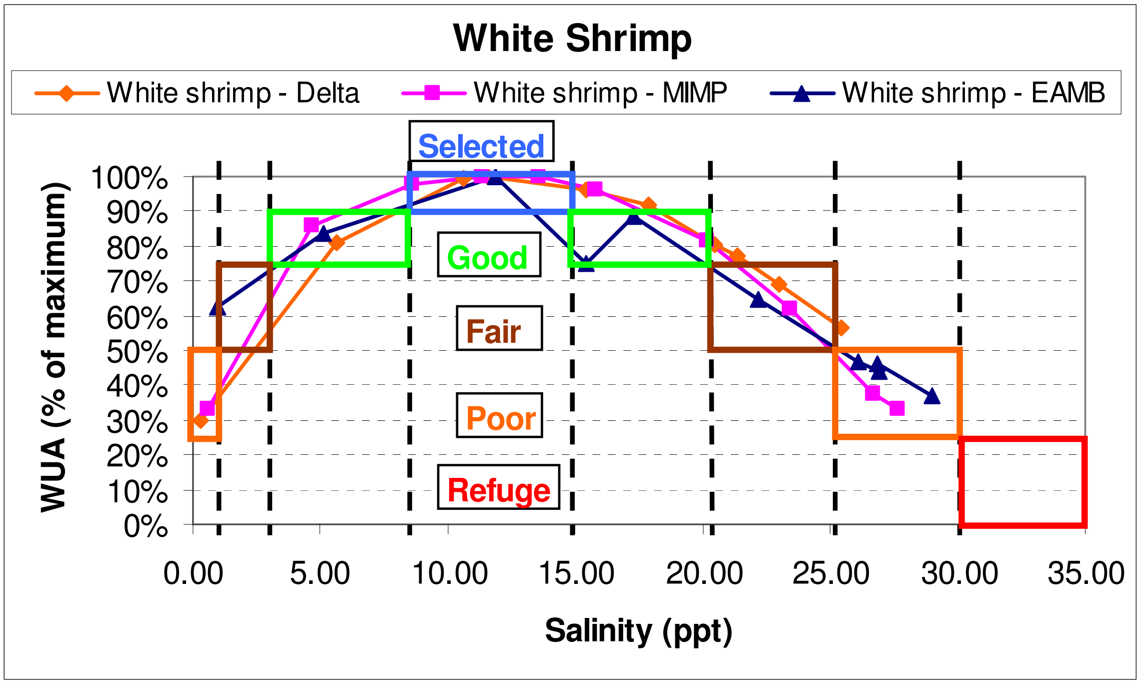


Figure 9. Habitat Model output – Percentage of Maximum WUA for white shrimp in the Delta, MIMP, and EAMB.

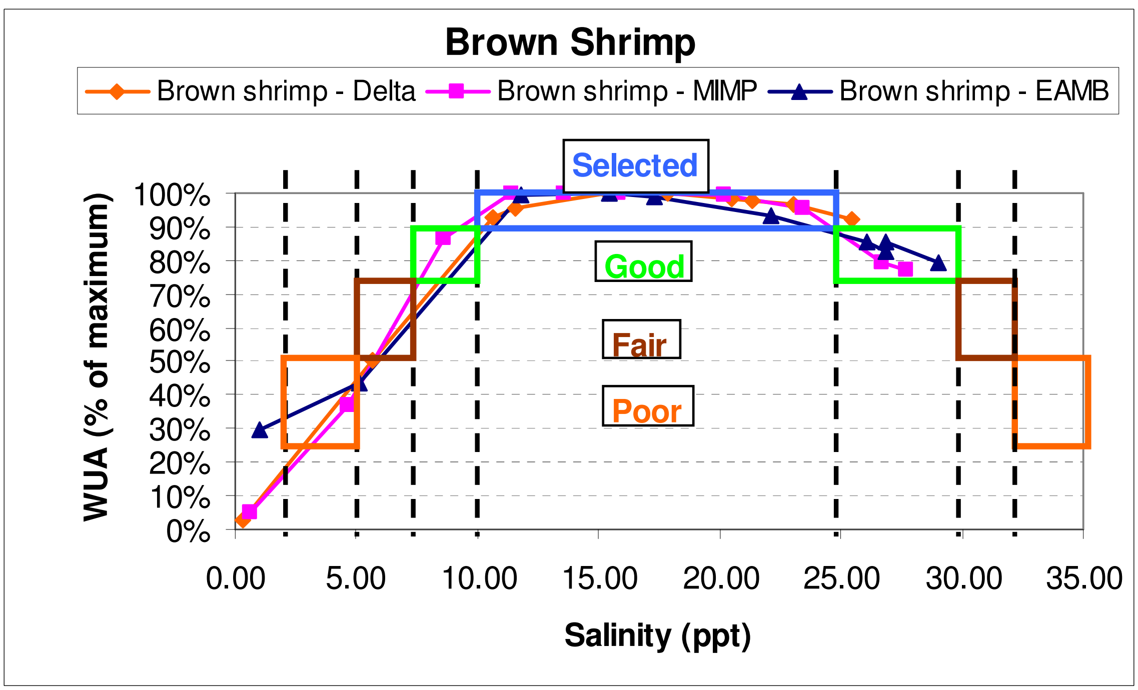


Figure 10. Habitat Model output – Percentage of Maximum WUA for brown shrimp in the Delta, MIMP, and EAMB.

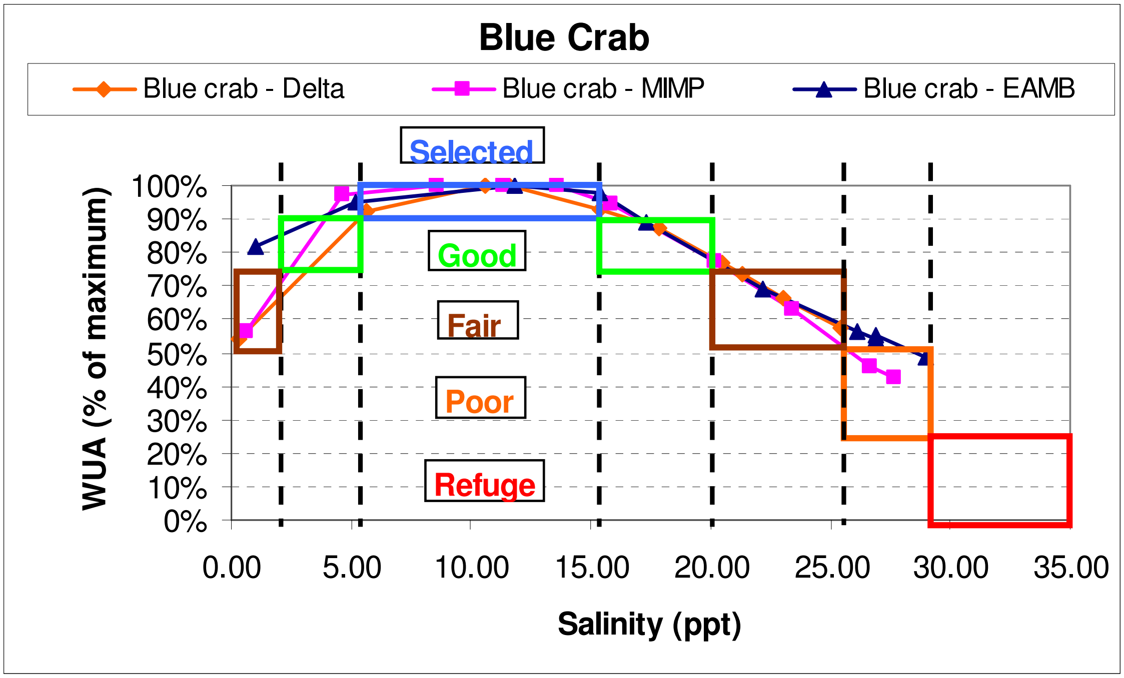


Figure 11. Habitat Model output – Percentage of Maximum WUA for blue crab in the Delta, MIMP, and EAMB.

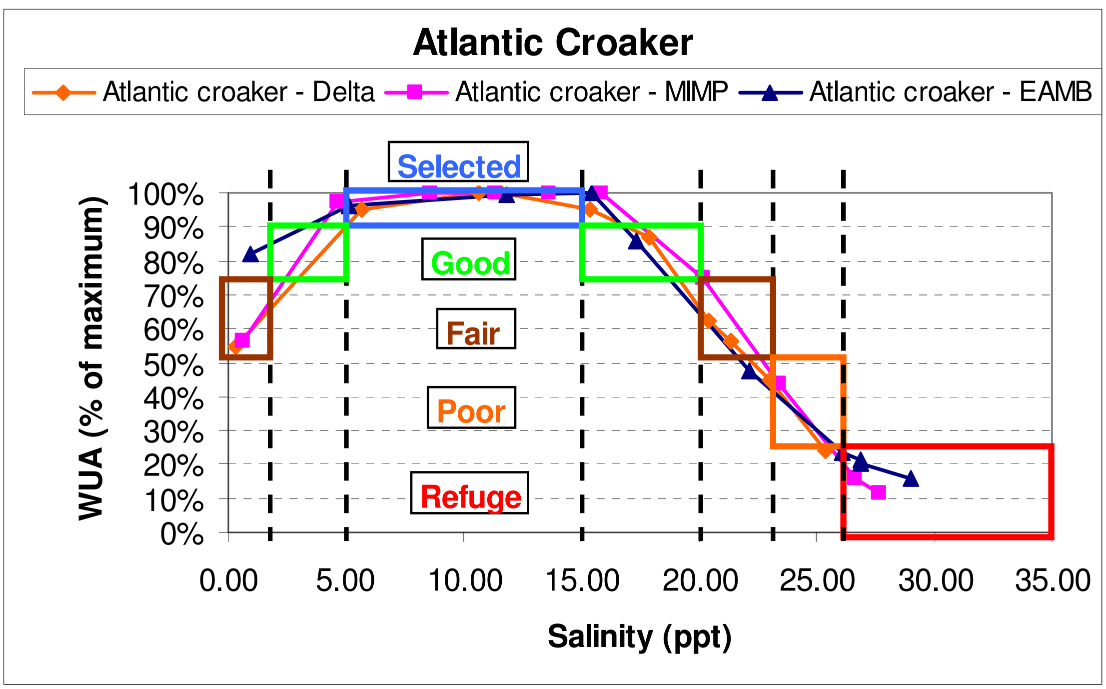


Figure 12. Habitat Model output – Percentage of Maximum WUA for Atlantic croaker in the Delta, MIMP, and EAMB.

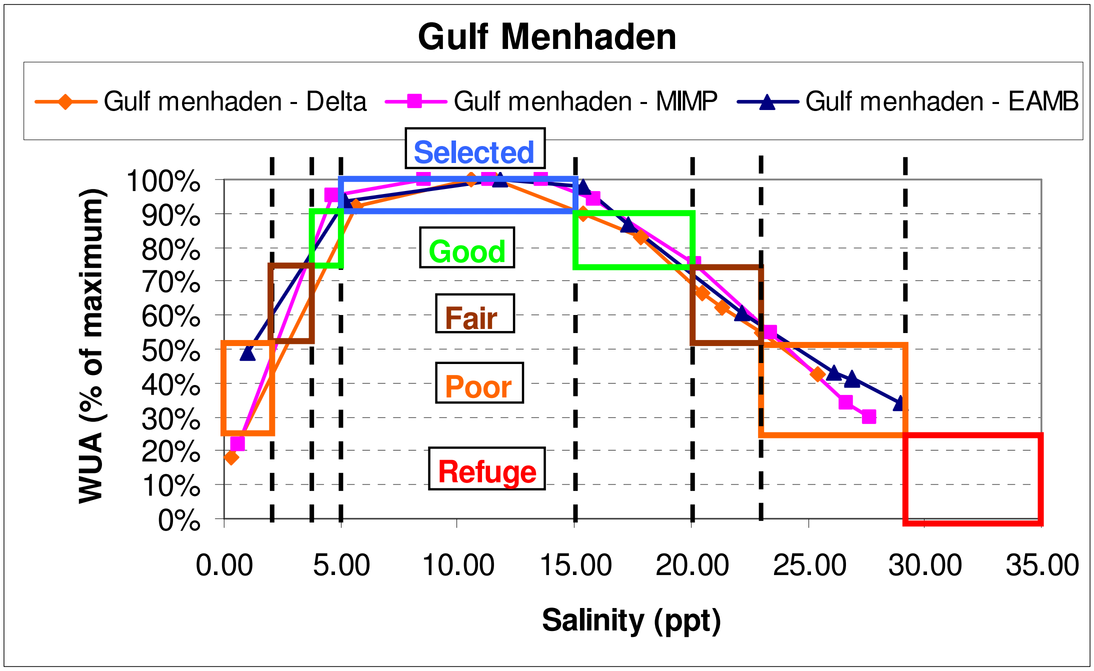


Figure 13. Habitat Model output – Percentage of Maximum WUA for Gulf Menhaden in the Delta, MIMP, and EAMB.

Figures 9 through 13 also demonstrate that the habitat model predicts lower levels of habitat quality for shellfish and forage fish at low salinities. Although a valid relationship, the focus of this task is on setting freshwater inflow criteria under manageable conditions. Since higher inflow (reduced salinity) periods are largely beyond human control, a low habitat quality ranking category for low salinities caused by high inflow events was not included in Table 1. It should be noted that although these higher inflow events do cause temporary declines in habitat availability, they do provide essential functions to the bay system, including sediment, organic matter, and nutrient influx.

Several key observations were noted during habitat modeling including the importance of low estuarine marsh habitats to shellfish, a sharp decline in habitat availability for most species (brown shrimp excepted) as conditions shift from estuarine to marine, and decrease in habitat availability at the salinity extremes. Additional model analysis (MBHE 2007a) allowed a spatial observation of changes and total WUA for the Delta along with the entire habitat model area (based on salinity conditions within the Delta). Also noteworthy is that condition changes within the Delta are driven primarily by Colorado River flows, while changes in other parts of the bay, particularly East Matagorda Bay (EMB), are more controlled by localized freshwater inflow. Therefore, habitat suitability across the entire bay area can vary spatially according to inflow, and different areas can potentially exhibit large differences in suitability during the same time period.

Another component of the analysis was the calculation of WUA for low estuarine marsh (annually) and each species per each month (during time in bay) for the long-term hydrodynamic/salinity model run (1995-2002). A detailed discussion of these results is also presented in MBHE 2007a. Overall, the results followed the same trends as observed in the model runs discussed above. Larger changes in WUA relative to dryer conditions were observed for blue crab, white shrimp, Atlantic croaker, and Gulf menhaden. Brown shrimp, however, observed the largest declines in WUA during fresher conditions. A review of the habitat model output for the long-term validation run by the month assisted the understanding of spatial distribution of habitat under different inflow regimes from 1995-2002 and also confirmed the importance of localized freshwater inflow into the Matagorda Bay system.

Finally, it is acknowledged that temperature and dissolved oxygen (DO) are also a vital component to the ecological understanding of the key species. However, as the LSWP is not anticipated to significantly alter temperature regimes or DO concentrations, complex temperature and DO models were not constructed. As such, including temperature or DO as parameters within the habitat model would not change model output because, under all scenarios, they would be held constant based on historical conditions. Interactions between salinity and temperature were included in the oyster modeling discussed in Section 2.3, and the benthic model discussed in Section 2.4.3. Additionally, the compounding influence of temperature and salinity on the key species is being considered within the LSWP climate change analysis.

2.3 Oyster Suitability Criterion Model

In the 2006 Habitat Progress report (MBHE 2006a), a number of oyster reef condition indices (CI) were developed as simple descriptors of the health of Eastern oysters, *Crassostrea virginica*, in areas potentially impacted by the LSWP. A long-term oyster database for the Matagorda Bay region was constructed by combining information from the TPWD oyster dredge database and the Dermo Watch database (also called the Oyster Sentinel database; http://www.oystersentinel.org). The combined derivative database contains monthly averages of parameters for reef locations in Matagorda, Galveston, and San Antonio Bays from 1996 through 2006 (non-Dermo Watch reefs) or 2007 (Dermo Watch reefs). Regression models were then developed to relate values of the CIs to salinity and temperature conditions in the database. These models can provide the framework for biological linkage of the health of Eastern oysters to the Matagorda Bay hydrodynamic/salinity model and for linking oyster condition to bay inflow criteria.

In 2007, two of the CIs were refined and selected for further use, while others were discontinued (MBHE 2007a). The database development, CI development and refinement, regression model development, and validation exercises were detailed in MBHE 2007a. The oyster database was further updated in early 2008 as described in Section 2.3.2. The two CIs are OCI (oyster condition index) and DCI (dermo condition index). OCI is an index of abundance of commercial-sized oysters, and DCI is an index of dermo infection level in commercial-sized oysters. Dermo is the common term for *Perkinsus marinus*, the most destructive oyster parasite in the Gulf of Mexico.

Currently, only DCI is being used for inflow criteria development. DCI was preferentially chosen over OCI because of the relatively high R^2 value of the DCI model as compared to the OCI model (MBHE 2007a).

The following equation was used to determine DCI from average dermo weighted incidence (DI) data for each month and reef location in the oyster database:

$$DCI = 1 - \frac{Log_{10}(DI + 1)}{Log_{10}(MaxDI + 1)}$$

where:

DI = Dermo weighted incidence, which is the average monthly dermo incidence index in sampled host oysters. DI was obtained from the online Dermo Watch database. The dermo incidence index is a unitless, qualitative index that ranges from 0 to 5 in individual oysters, with 0 = no dermo infection and 5 = maximum pre-mortality parasite load. Note: DI is referred to as "Dermo Intensity" in prior MBHE reports.

MaxDI = An average dermo weighted incidence of 3.25.

The value of *MaxDI* was chosen with respect to the maximum historically observed average dermo weighted incidence in the online Dermo Watch database among the reefs that were selected for DCI model development. *MaxDI* was chosen to be slightly higher than the maximum observed oyster database value of 2.7, so that values of DCI were unlikely to exceed 1, but that high levels of dermo weighted incidence resulted in DCIs close to 1. As indicated by the structure of the DCI equation, DCI can range from 0: worst condition (average oyster parasite load as high as the historically highest parasite load), to 1: best condition (no parasites in commercial-sized oysters). Note that the maximum dermo weighted incidence is only about half the maximum dermo incidence possible in individual oysters. This is because an oyster population, which contains a range of weighted incidence levels and individuals with a dermo weighted incidence of 4 or 5, quickly dies off.

Development of the 2007 multiple regression model that best predicted DCI was detailed and discussed in MBHE 2007a. The model predicted 61% of the spatial and temporal variation in DCI (model R^2 = 0.610) using three parameters as shown in the following equation:

$$DCI = 2.604 - 0.02973(2YS) - 0.08935(2YWT) - 0.01145(3MRAT)$$

where:

2YS = two-year average salinity (an average of three-month seasonal averages)

2YWT = two-year winter temperature average (An average of monthly averages; designated winter months were December, January, and February.)

3MRAT = three-month rolling temperature average (An average of monthly averages)

The equation shows that DCI decreased with increasing two-year average salinity (2YS), the biological explanation being that the dermo parasite has poor growth in low salinities and grows well in high salinities. DCI also declined with two-year winter temperature (2YWT), and three-month rolling average temperature (3MRAT) as indicated by the second and third model parameters after the intercept. Negative temperature effects were expected as dermo growth within the host oyster is strongly affected by temperature, with higher temperatures leading to higher parasite growth rates, hence poorer oyster condition.

A short-term temperature parameter such as 3MRAT had not been included in the previous DCI model (MBHE 2006a), but was considered a biologically plausible term to include because of the strong effect of temperature on dermo division rate, the short generation time of the parasite, and the typical seasonal pattern of lower dermo weighted incidence in colder months (MBHE 2007a).

2.3.1 DCI Behavior at Extremes

The behavior of DCI at extreme temperature and salinity conditions was evaluated for the tendency for the occurrence of predicted DCI values outside of the intended 0 – 1 range. To test behavior at extremes, frequency distributions of temperature and salinity parameters in the regression model were obtained from 1996 – 2006 from all reef locations in the oyster database. Values from these distributions were used to determine DCI predicted for the three input parameters at the extremes of the parameter distributions (tested 99.5, 97.5, 90, 10, 2.5, and 0.5 quantiles). The DCI model returned index values > 1 when all three model terms were at low extremes and < 0 when all three model terms were at high extremes. A combination of extremes is unlikely to occur given that the combined probability of three rare events is extremely rare, but in the event that it occurs, DCI will be assigned values of 0 or 1 beyond the 0 - 1 range. Therefore, the finalized model for determining DCI was:

$$DCI = 2.604 - 0.02973\,(2YS) - 0.08935\,(2YWT) - 0.01145\,(3MRAT)$$

$$If\ DCI < 0,\ then\ DCI = 0;\ If\ DCI > 1,\ then\ DCI = 1$$

2.3.2 2008 DCI Refinements

It was noted by TPWD during the review process that there were apparent errors in the online Dermo Watch database. As a result, the Dermo Watch program conducted a check of their database and subsequently posted an updated database in 2008. Errors included switched temperature and salinity data for all reefs in Galveston Bay from July 2002 through December 2003 and removal of some problematic records from late 2004 through mid-2005 for nine reefs in Matagorda and Lavaca Bays. While correcting the oyster database for these errors, the opportunity was taken to add the 2007 Dermo Watch data for salinity, temperature and dermo weighted incidence to the database. Then the multiple regression model was reconstructed using the updated and corrected database.

The resulting best new DCI regression model was:

$$DCI = -0.5807 - 0.04825\,(2YS) + 0.09792\,(2YSPT) - 0.009627\,(3MRAT)$$

$$If\ DCI < 0,\ then\ DCI = 0;\ If\ DCI > 1,\ then\ DCI = 1$$

where:

2YS = two-year salinity average.

2YSPT = two-year spring temperature average (designated spring months were March, April, and May).

3MRAT = three-month rolling temperature average.

Model R^2 = 0.56. The regression model is displayed graphically in Figure 14.

The notable difference between the former and current model was that two-year spring temperature was included instead of the two-year winter temperature. Furthermore, DCI increased (i.e. dermo weighted incidence decreases) with increasing spring temperatures, which is opposite to the expected simple effect of increased dermo with higher temperatures (discussed above). However, extensive mechanistic oyster population models developed by Hofmann, Powell and colleagues [i.e., Hofmann et al. 1992, Powell et al. 1995) concluded that in warm springs with consequently early spring phytoplankton blooms, oysters can 'outgrow' their dermo infections to some extent because temperatures are still relatively cool for the parasite (as compared to summer), while they are ideal for the food supply and physiology of the host. Therefore the positive effect of spring temperatures was deemed biologically plausible even though the direct effect of warmer temperatures is to increase dermo growth rate and, hence, dermo weighted incidence in the host. Note that three-month rolling temperature average still has a negative effect, as discussed above.

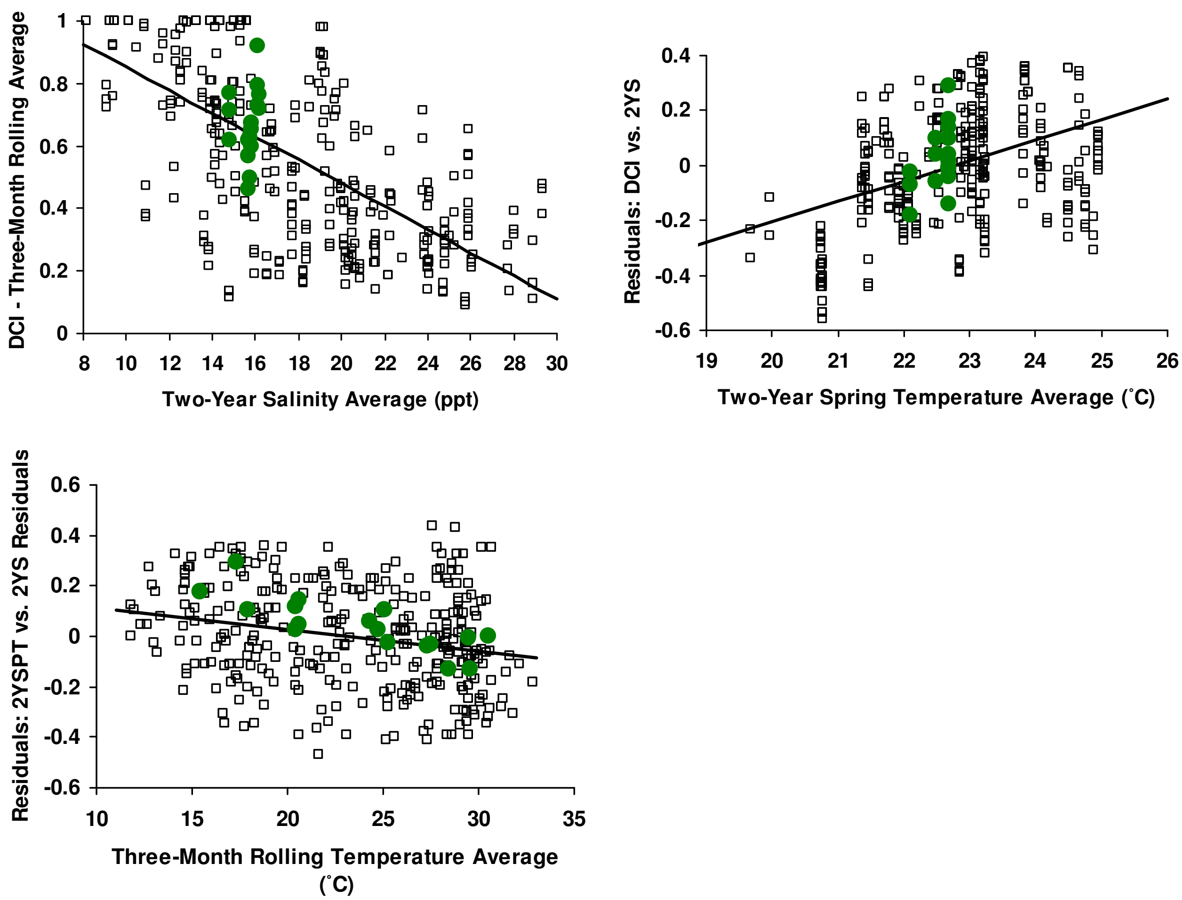


Figure 14. Graphic presentation of multiple regression model for DCI. Top Left: Three-month rolling average of DCI predicted by two-year average salinity. Top Right: Residuals of the top left plot predicted by two-year spring temperature average. Bottom: Residuals of top right plot predicted by three-month rolling average temperature. Data points from EAMB reefs are shown as large green circles.

2.3.3 DCI Response to Salinity

For the purpose of inflow criteria evaluation, the DCI model was used to evaluate salinity ranges that would protect oyster reefs within selected areas. Discussions were held with Dr. Thomas Soniat, head of the Dermo Watch program, to determine what levels of dermo weighted incidence should be protected to maintain oyster reef health. A dermo weighted incidence of 1 (scale of 0 – 5) provides only a slight level of concern for the oyster reef and thus dermo levels <1 were selected as representative of high quality oyster reef condition. A dermo weighted incidence of 2 invokes greater concern about reef health and has the potential for extensive oyster mortality should conditions persist. Therefore, dermo weighted incidence values around 1.5 were considered moderate and dermo weighted incidence values >2 were considered poor conditions. These threshold dermo weighted incidence values of 2, 1.5, and 1 are presented as horizontal lines in Figure 15, and DCI model results from various combinations of model salinity and temperature parameters were evaluated with respect to these values as described below.

For the inflow regime criteria analyses, the DCI model equation in Section 2.3.2 was used to obtain predicted DCI values and corresponding weighted incidence values back calculated using the equation in Section 2.3. Predicted weighted incidence values were calculated for 2YS ranging from 10ppt to 35ppt in combination with median or extreme temperature conditions (two-year spring temperature [2YSPT] and 3MRAT). The temperature range considered was based on historical temperature distributions in the EAMB (Table 2). Four specific temperature scenarios were evaluated in Table 3, and results are presented in Figure 15.

Table 2. Frequency distributions of monthly average values of the two DCI model temperature parameters from four reef locations in the EAMB from 1996 through 2007. Sample size is 390 for 2YSPT and 305 for 3MRAT. Data are from the TPWD Coastal Fisheries Database and from the Dermo Watch database.

Frequency Distribution Quantile	Two-Year Spring Temperature Average (˚C)	Three-Month Rolling Temperature Average (˚C)
100%	25.30	31.13
90%	25.11	29.63
75%	24.03	28.18
50%	22.98	24.21
25%	22.09	18.13
10%	21.22	14.72
0%	19.15	10.58

Table 3. Combinations of temperature parameters evaluated for DCI model predictions. Evaluation results are shown in Figure 15.

Historical Condition	2YSPT Quantile	3MRAT Q Quantile	Comment
Good	90th	10th	High 2YSPT and low 3MRAT have been related to lower dermo weighted incidence
Typical	50th	50th	Median Conditions
Somewhat Poor	50th	90th	Median long-term temperature condition with poor short-term temperature condition
Very Poor	10th	90th	Low 2YSPT and high 3MRAT have been related to higher dermo weighted incidence

As evident in Figure 15, there is an interaction between the two water temperature parameters and the salinity levels that relate to specific predicted dermo conditions. With "good" temperature conditions, a higher range of salinities could be tolerated by the oysters and vice versa.

DCI results are related to cumulative salinity conditions over a two-year period rather than single time point salinity measures. It is therefore not correct to predict DCI results from a range of single time point salinities, primarily because the distribution of two year rolling averages of salinities is skewed lower than the distribution of single time point salinities due to the effect of including low salinity extremes from freshets into the two-year averages. The DCI model approach is considered appropriate because development of dermo infection is a multi-year phenomenon due to both the effect of prior infection levels on current infection levels for the whole reef population, and to the multi-year life span, and consequent effect of prior infection level, within individual host oysters (T. Soniat 2008). The two-year average importantly allows for effects of freshet events to be incorporated into dermo predictions, and two-year salinity average accounts for 41% of the historical temporal and spatial variation in dermo weighted incidence in the oyster database (partial R^2 of 2YS = 0.41).

Since, this application does not apply to single time point salinity or temperature values, using this tool for management decisions will require the concurrent implementation of long-term monitoring of salinity, temperature, and dermo weighted incidence at select reefs throughout the Matagorda Bay system. With long-term monitoring in place, not only could the model be improved over time, but the real-time measurements could also be used to inform and predict oyster reef health in these areas.

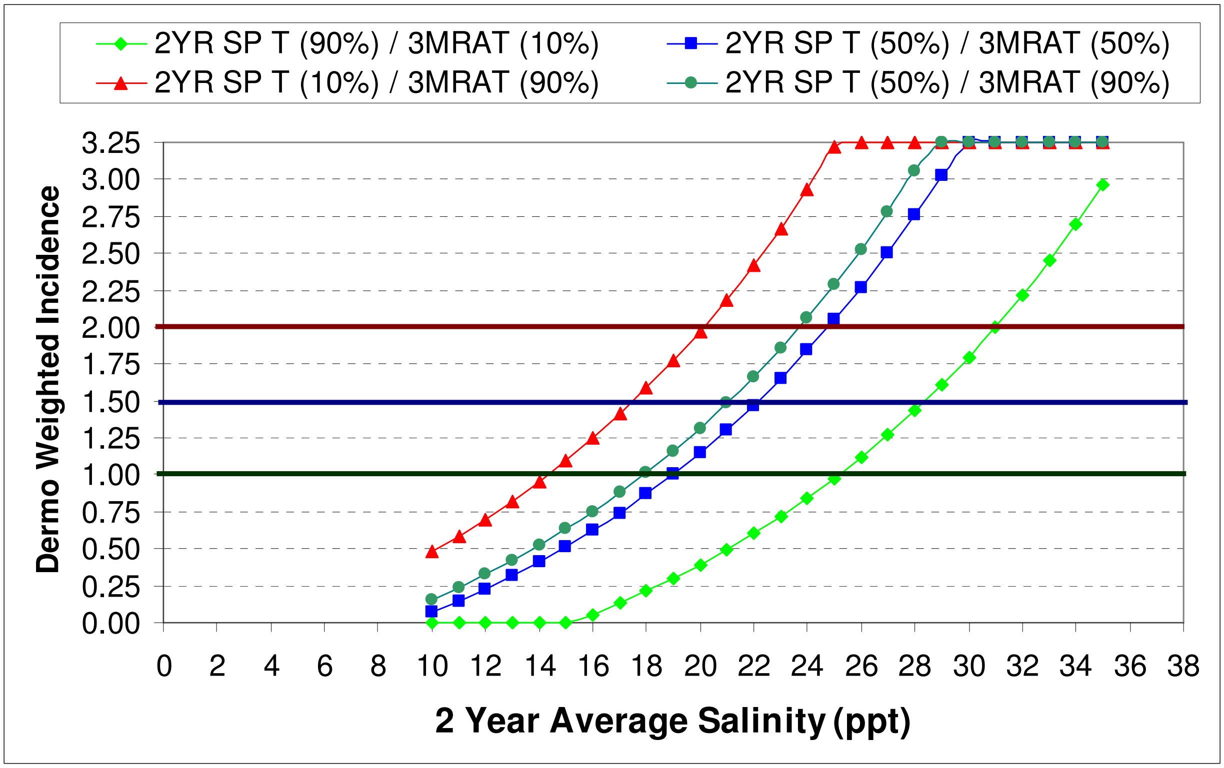


Figure 15. DCI model results: two-year rolling salinity versus predicted dermo weighted incidence for four temperature regimes (described in Table 3) representing average and extreme temperature conditions. Horizontal lines represent levels of dermo weighted incidence considered to have low (1.0), model.

2.4 Benthic Analysis

Benthic condition in this section refers to the status of macroinfaunal community structure and function. Macroinfauna is a compound term from the words macrofauna and infauna, which are the small bottom-dwelling invertebrates (retained on a 0.5 mm sieve) extracted from bay bottom sediments. Macrofauna are good indicators of environmental condition because they are relatively long-lived, sessile, live in the bottom, and respond to food from above; thus macrofauna integrate effects caused by changes in the overlying water over long time periods. Diversity is an indicator of structure, and productivity is an indicator of function, therefore when diversity and productivity are stable over long periods of time, the ecosystem is sustainable and thus healthy. Three studies have been performed that are used to support an assessment of benthic condition for the MBHE. These studies include an analysis of long-term benthic community structure data (Montagna 2008), characterization of benthic habitat variability in the Matagorda Bay area (Montagna et al. 2006a), and a modeling study to predict benthic productivity as it would relate to salinity and nutrient changes in Matagorda Bay (Montagna 2008). Combined, the results of these studies allow a quantitative assessment of the potential for change to benthic condition that result from changes in salinity habitat condition.

2.4.1 Long-Term Benthic Community Structure

Benthic macrofaunal community structure was studied from 1988 through 2007 to determine response to changes in inflow in Lavaca and Matagorda Bays (Montagna 2008). Six stations were sampled along freshwater inflow gradients emanating from the Lavaca and Colorado Rivers (Figure 16). In the western portion of the estuary, the Lavaca River generates a fresh-to-marine salinity gradient, with station A (28° 40′ 12″ N, 96° 34′ 48″ W) and B (28° 38′ 24″ N, 96° 34′ 48″ W) located in the highly freshwater-influenced portion of Lavaca Bay. Intermediate station C (28° 32′ 24″ N, 96° 28′ 12″ W) is located mid-way between Lavaca and Matagorda Bay, while marine-influenced station D (28° 28′ 48″ N, 96° 17′ 24″ W) is located near the Matagorda ship channel pass. In the eastern portion of the estuary, the lower Colorado River generates another fresh to marine salinity gradient in Matagorda Bay, where stations D, E (28° 33′ 0″ N, 96° 12′ 36″ W), and F (28° 36′ 0″ N, 96° 02′ 24″ W) are located. Although stations A - D have been sampled from 1988 (Kalke and Montagna 1991; Montagna and Kalke 1995), all analyses for the current study were performed using a balanced design where stations A - F were sampled synoptically. These data represent the periods of time from April 1993 - July 2000 and July 2004 - October 2007.

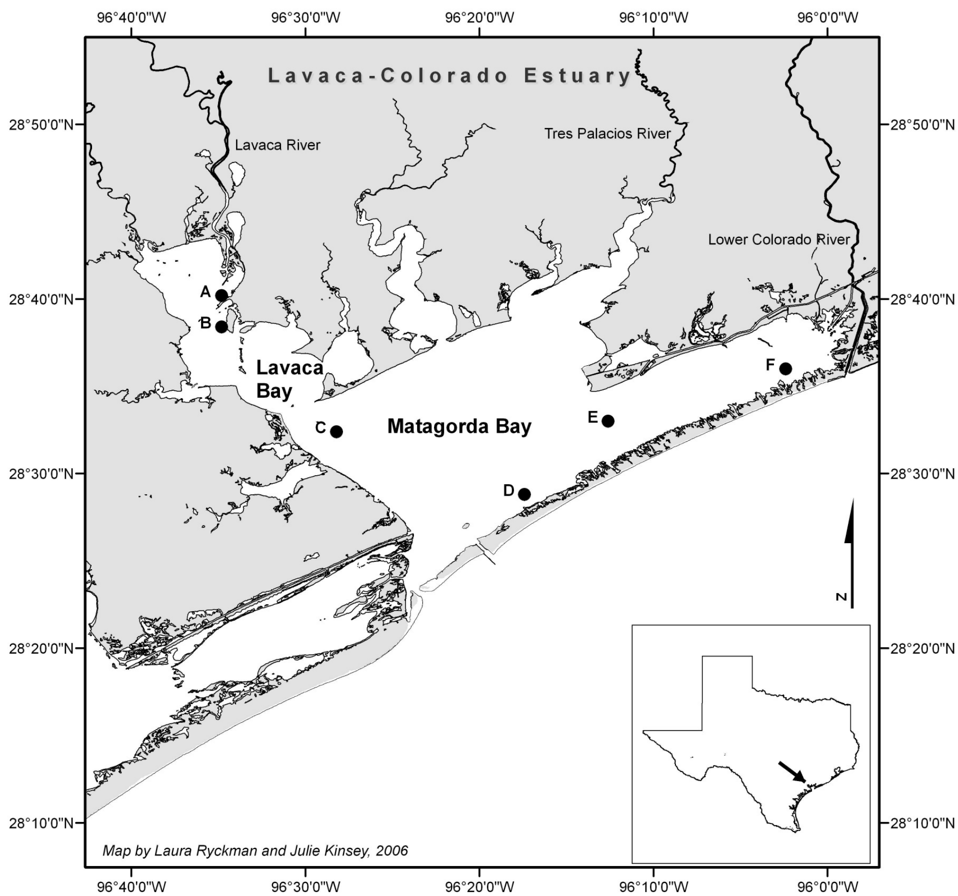


Figure 16. Study area sampling stations.

In general, the primary bay (Matagorda Bay) stations exhibit higher biomass than the secondary bay (Lavaca Bay) stations (Figure 17). Mean biomass was lowest at freshwater-influenced stations A

(1.03 g m^{-2}) and B (0.94 g m^{-2}), intermediate at station C (2.44 g m^{-2}), and greatest at station D (5.76 g m^{-2}), located in the most marine-influenced area. Mean biomass at stations E (3.56 g m^{-2}) and F (3.19 g m^{-2}) was also relatively high. The long-term data show strong year-to-year variability and declines in biomass values over time are observed at all stations. There is a direct relationship between freshwater inflow and salinity on benthic communities. High inflow is directly related to low salinity and high nutrient levels in the system as well. Significant relationships are also found between univariate measures of community structure between flood and drought periods, and distinct station differences in community structure along salinity gradients.

Over 70% of all species found comprised polychaetes, while crustaceans constituted 5% and bivalves 7%. The polychaete *Mediomastus ambiseta* dominated overall, representing 45% of the entire species pool. The next most abundant species were the polychaetes *Polydora caulleryi* at 9% and *Streblospio benedicti* at 8%. Out of a total of 202 species, 22 species represented 91% of all of the individuals found over all stations.

Six indicator taxa of freshwater inflow effects were identified; all were aquatic insects, most being chironomid species of different life stages. Although aquatic insects are the best indicator of fresh conditions, these organisms were never dominant, contributing < 0.1% of the total organisms sampled. Five brackish water indicator species were also identified: the polychaetes *Streblospio benedicti* and *Parandalia ocularis*, the crustacean *Ampelisca abdita*, and the bivalves *Macoma mitchelli* and *Mulinia lateralis*. Lastly, five marine indicator species were identified: a crustacean *Apseudes* sp., the bivalves *Corbula contracta* and *Periploma cf. orbiculare*, the polychaete *Minuspio cirrifera* and the brittle star *Amphiodia atra*.

Distinct benthic community differences in abundance, biomass, diversity, and species composition are found among the study stations along both the Lavaca River and Colorado River salinity gradients, allowing communities to be defined by three salinity zones: a mixo-mesohaline (freshwater) zone of 5 – 18 ppt (Lavaca Bay stations A and B), a mixo-polyhaline (intermediate) zone of 18 – 30 ppt (Matagorda Bay station C), and euhaline (marine) zone of 30 -40 ppt (Matagorda Bay station D). These salinity regimes act as a proxy for measuring the effects of freshwater inflow, and the results indicate that benthic communities respond to changes in inflow and do so in a relatively predictable manner. Community differences were less defined along the Colorado River salinity gradient than along the Lavaca River gradient. Station E (where the eastern arm of West Matagorda Bay opens to the bay proper) alternated between intermediate and marine community structure, whereas station F (nearer the Colorado River) oscillated between freshwater and intermediate community structure.

Principal Component Analysis (PCA) was used to assess relationships between hydrologic variables. Principal Components 1 and 2 (PC 1 and PC 2) for the water-column variables explained 47% and 20% of the variation within the data set (total 67%; Figure 18). The PC 1 variable loads have the highest positive values for oxidized inorganic nitrogen (N+N = NO_2 + NO_3), ammonium (NH_4), and phosphate (PO_4), and the highest negative values for salinity. Low salinity is correlated to high nutrients, thus PC 1 represents a linear scale of freshwater inflow effects. High temperature is correlated to low dissolved oxygen (DO) along PC 2, thus PC 2 represents seasonal effects. Positive PC 2 variable loads for silicate (SiO4) are likely due to increased sediment re-suspension as a function of seasonal wind patterns. Station loading scores are distributed in a fairly distinct spatial pattern into two inflow zones, with freshwater zones A, B, and F generally exhibiting the most negative relationship with salinity and marine zones C, D, and E being most positive.

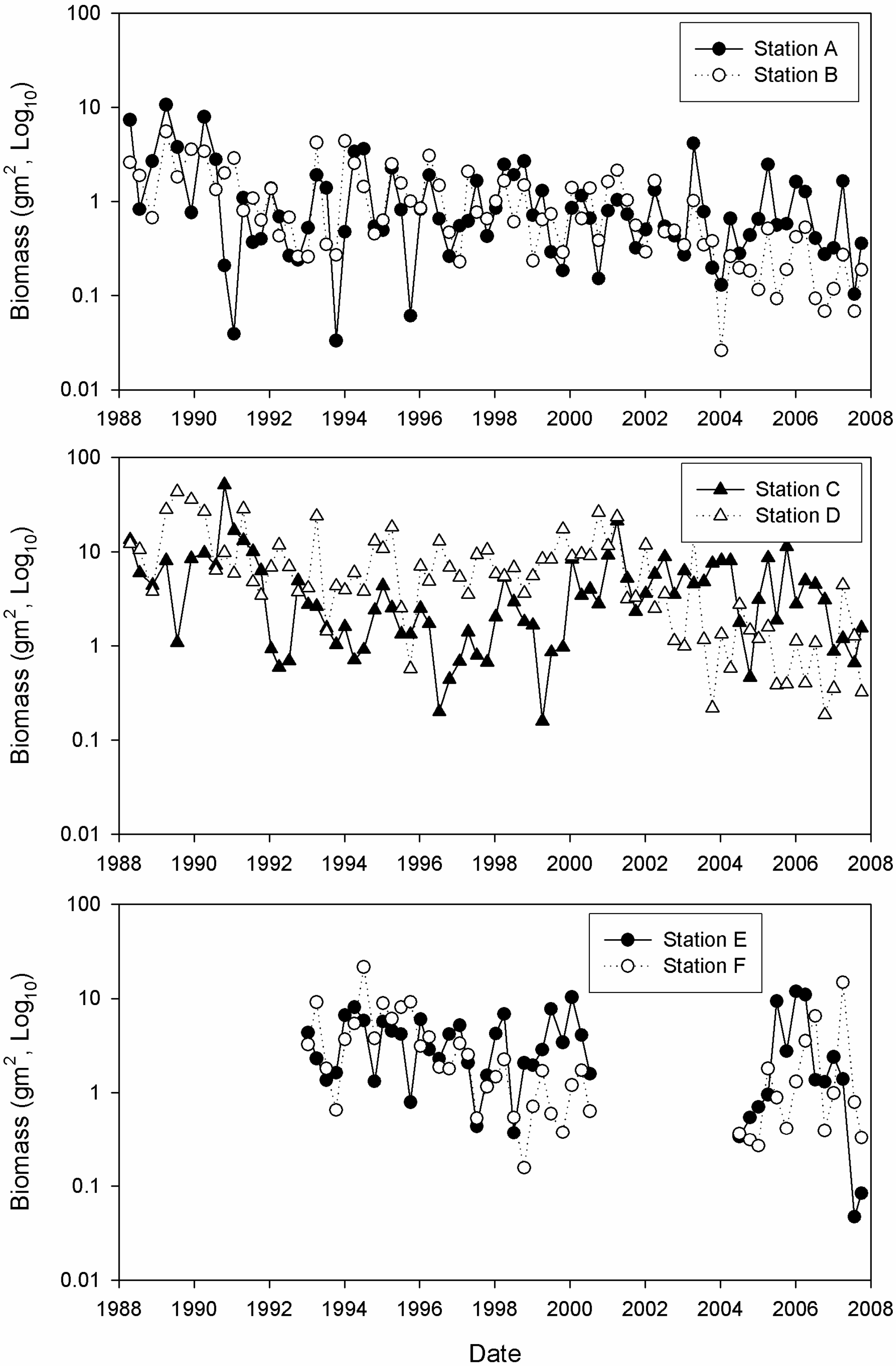


Figure 17. Biomass (g m^{-2}, log10) at Stations A-F from April 1988 - October 2007.

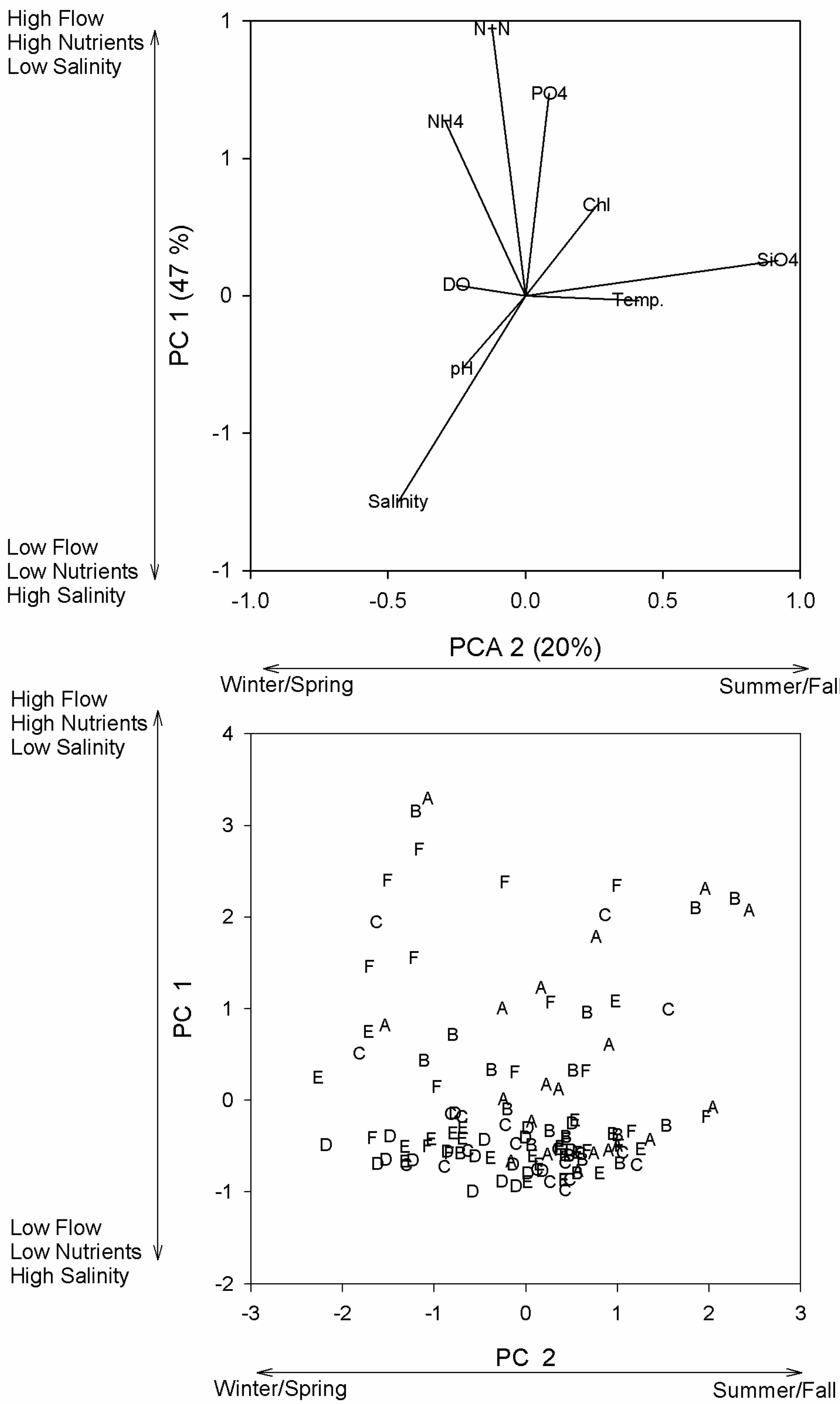


Figure 18. PCA variable loads (top) and stations-date scores (bottom) for hydrographic characteristics, symbols are station names.

Non-metric multidimensional scaling (MDS) was used to illustrate similarities between communities on different sampling periods or between stations. Results of the MDS analysis show that benthic communities are generally spatially distinct along the salinity gradient of the study area (Figure 19). Macrofaunal communities are divided into 2 large zones, with at least 30% similarity among stations in each zone; stations tend to group left to right with increasing salinities. Zone 1 contains all of the samples collected at freshwater-influenced stations A, B, and F. Zone 1 also overlaps with zone 2. Zone 2 contains most of the samples from intermediate station C, as well as marine stations D and E. Station F oscillates between freshwater and intermediate community structure, while station E alternates between intermediate and marine community structure. Samples that group into the other 3 zones (3, 4 and 5) are primarily due to differences in seasonal sampling.

2.4.2 Characterization of Benthic Variability

In April 2006, sampling was performed over broad spatial scales in Matagorda Bay to determine how well the six long-term stations characterize the spatial variability of benthic communities directly influenced by the Colorado River (Montagna et al., 2006a). Samples were collected from 18 stations to measure benthic community structure, hydrographic characteristics (depth, salinity, temperature, nutrients, and chlorophyll), and sediment characteristics (grain size, carbon and nitrogen content). Adjacent to the Colorado River, water quality and water column depth had higher correlations with macrobenthic community structure than sediment characteristics, but sediments were important overall. At a 40% similarity level, macrobenthic communities were divided into five groups based on distance from the freshwater source, distance to the Gulf of Mexico, and bottom depth. Benthic communities in sheltered shallow habitats (< 0.5 m) were not represented by the current long-term stations, however all other community groups were represented. Apart from areas close to the Gulf Intracoastal Waterway and within 5 km of the Colorado River mouth, water quality in Matagorda Bay was well-characterized by the six long-term stations in low inflow conditions. Therefore, conclusions based on the long-term stations represent generality for the soft-bottom bay habitats in the areas deeper than 0.5 m.

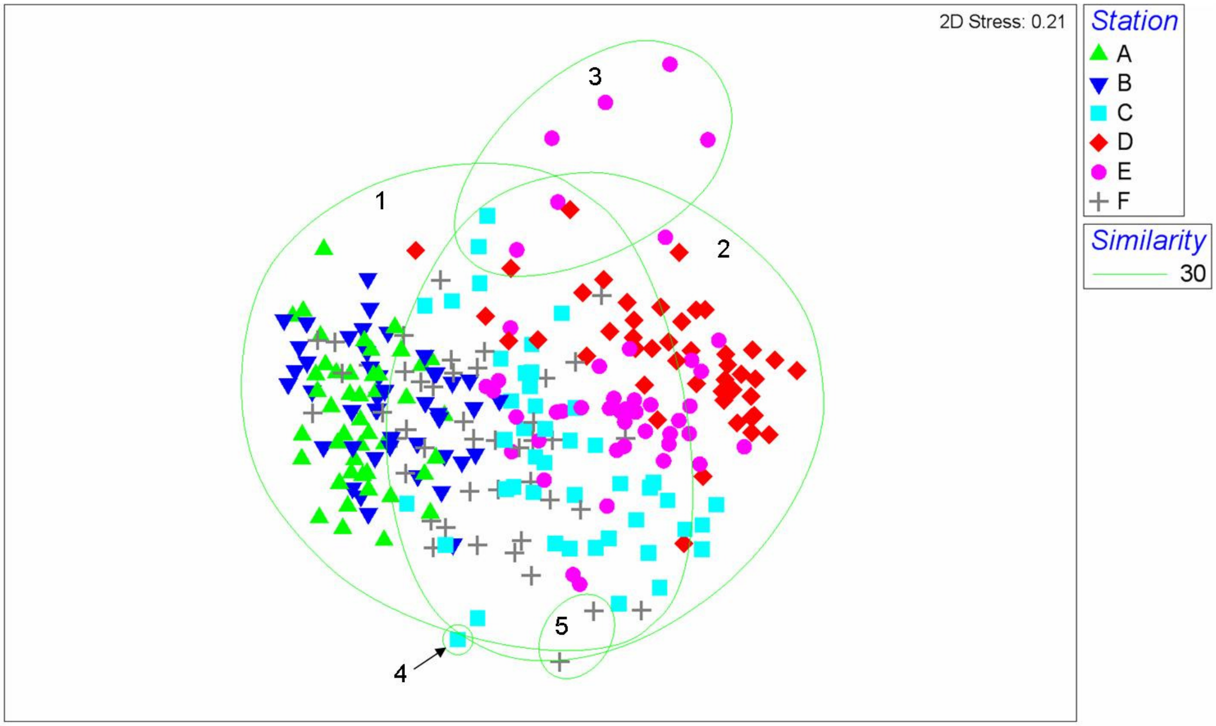


Figure 19. MDS analysis of species-level community structure including all sampling periods and stations.

2.4.3 Benthic Productivity Modeling

A bio-energetic model, calibrated using the long-term data set of benthic biomass, was run to relate macrobenthic biomass change to salinity within the Matagorda Bay area (aka, the Lavaca-Colorado Estuary) (Montagna et al. 2006b; Montagna 2008). This model was applied to the current study to assess the role of freshwater inflow in controlling benthic productivity, which is an indicator of ecological function. The modeling study complements the studies of ecological structure. Benthic productivity was calculated for two groups of macrobenthos (suspension feeders and deposit feeders) in two bays (Lavaca Bay and Matagorda Bay). The model was calibrated for the data period of 1988-1999. To evaluate the model performance the percent root mean square (RMS) difference was calculated between model outputs and observations from an independent data set (January 2000 – April 2005) for validation of the model. The formulation of RMS is:

$$\%RMSD = \sqrt{\frac{\sum \frac{(X_{mod} - X_{obs})^2}{N}}{\sum \frac{(X_{obs})^2}{N}}} \times 100$$

where X_{mod} and X_{obs} are model simulations and data, respectively. N is the size of the sample (i.e., number of individual data points), which is 22 data points for Lavaca and 24 for Matagorda Bay, respectively. The percent RMS differences between the simulated and observed biomass for deposit and suspension feeder in Lavaca Bay were 58.2% and 79.9%, respectively. When the model simulations and observations in Matagorda Bay were compared, there was a difference of only 69.6% for the deposit feeders and 78.3% for the suspension feeder biomass. The deposit feeder biomass simulation in Lavaca Bay was the best result among the four simulations and the suspension feeder simulation in Lavaca Bay had the worst fit (Table 4). The low RMS values indicate the model performance with calibrated parameters was successful.

Table 4. The percent root mean square (RMS) difference between observed and simulated benthic biomass.

Periods for comparisons	**Lavaca Bay**		**Matagorda Bay**	
	Deposit Feeders	**Suspension Feeders**	**Deposit Feeders**	**Suspension Feeders**
January 2000 - April 2005 (for validation)	58.2	79.9	69.6	78.3
April 1988 – April 2005 (for long-term simulation)	86.8	98.7	64.1	83.1

Simulations of both bays and feeding groups from April 1988 through April 2005 were compared to observed benthic macrofauna biomass data (Figure 20). The percent RMS differences was determined in Lavaca Bay and Matagorda Bay for deposit feeders and suspension feeders (Table 4). The simulations for both bays and each feeding group fit the observed data relatively well during the entire period, 1988 - 2005 (Figure 20).

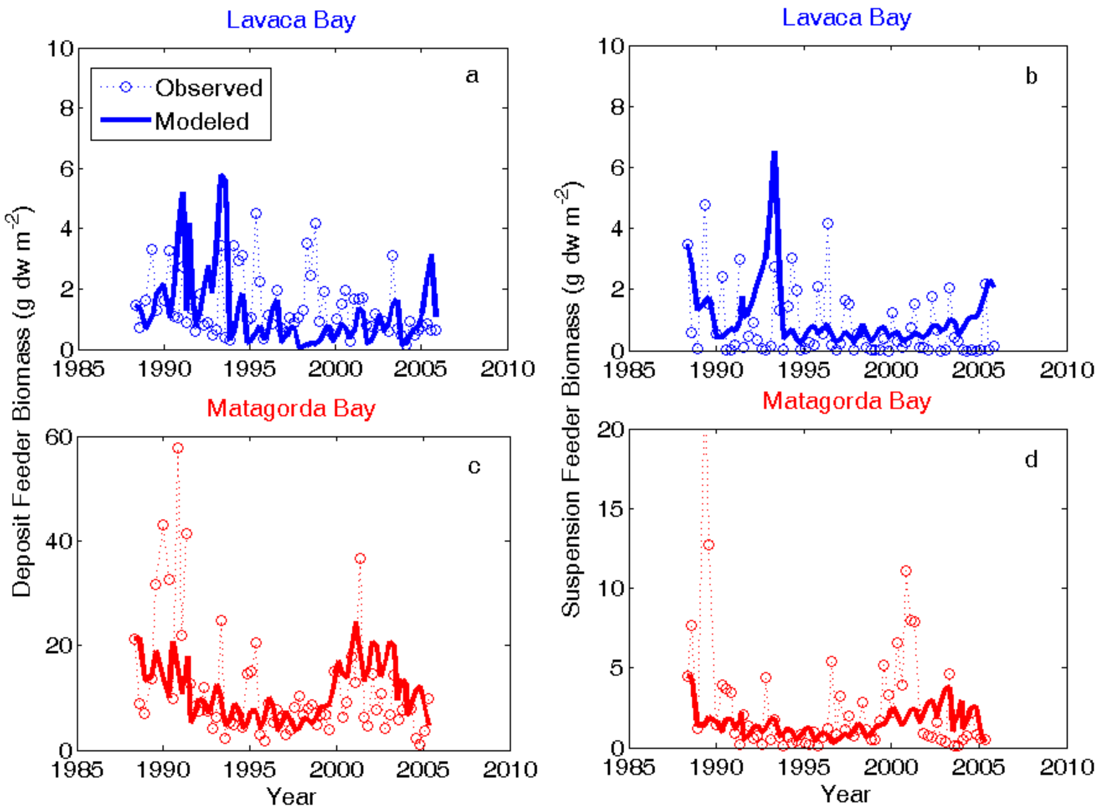


Figure 20. Comparisons between observed (dashed line with open circles) and modeled (solid lines) results in Lavaca and Matagorda Bay for the period 1988 -2005. (Deposit feeder biomass – panels (a) and (c) and suspension feeder biomass – panels (b) and (d)).

To investigate potential effects of ecological responses to freshwater inflow changes, deposit and suspension feeder biomass in Lavaca Bay and Matagorda Bay were also simulated. The combined effect of increased salinity and decreased nutrient concentrations was investigated to see how benthic energetics in both bays respond to inflow changes. This sensitivity test was performed with a 2%-interval so that salinity changes were ranging from -30% to 30% from original observations (e.g., combinations of original salinity $\pm$30% and original nutrients $\pm$30% every 2% intervals). Therefore, the simulations predict benthos biomass based on the following scenario: what if the salinity had been higher (or lower) and at the same time the nutrients had been lower (or higher) than they were over the historical period (i.e., 0% change)? As salinity increased and nutrients decreased simultaneously, deposit feeder biomass in Lavaca Bay showed a slight increase from -30% and up to 0% change, and then a slight decrease after 10% change (Figure 21). The model predicted an increase in deposit feeder biomass with increasing salinity clearly in Matagorda Bay (Figure 21). However, increased salinity resulted in decreased suspension feeder biomass in both Lavaca Bay and Matagorda Bay (Figure 21).

Total biomass concentration was calculated by adding deposit and suspension feeder biomasses (Figure 2). Lavaca Bay total biomass slightly decreased (0.5 g dry weight m^{-2}) with increasing percent change in salinity (and decreasing nutrients) (Figure 22a) because the decrease in suspension feeders was large compared to the increase in deposit feeders. In Matagorda Bay, biomass had a logistic-type increase (4 g dry weight m^{-2}) with salinity/nutrient change following

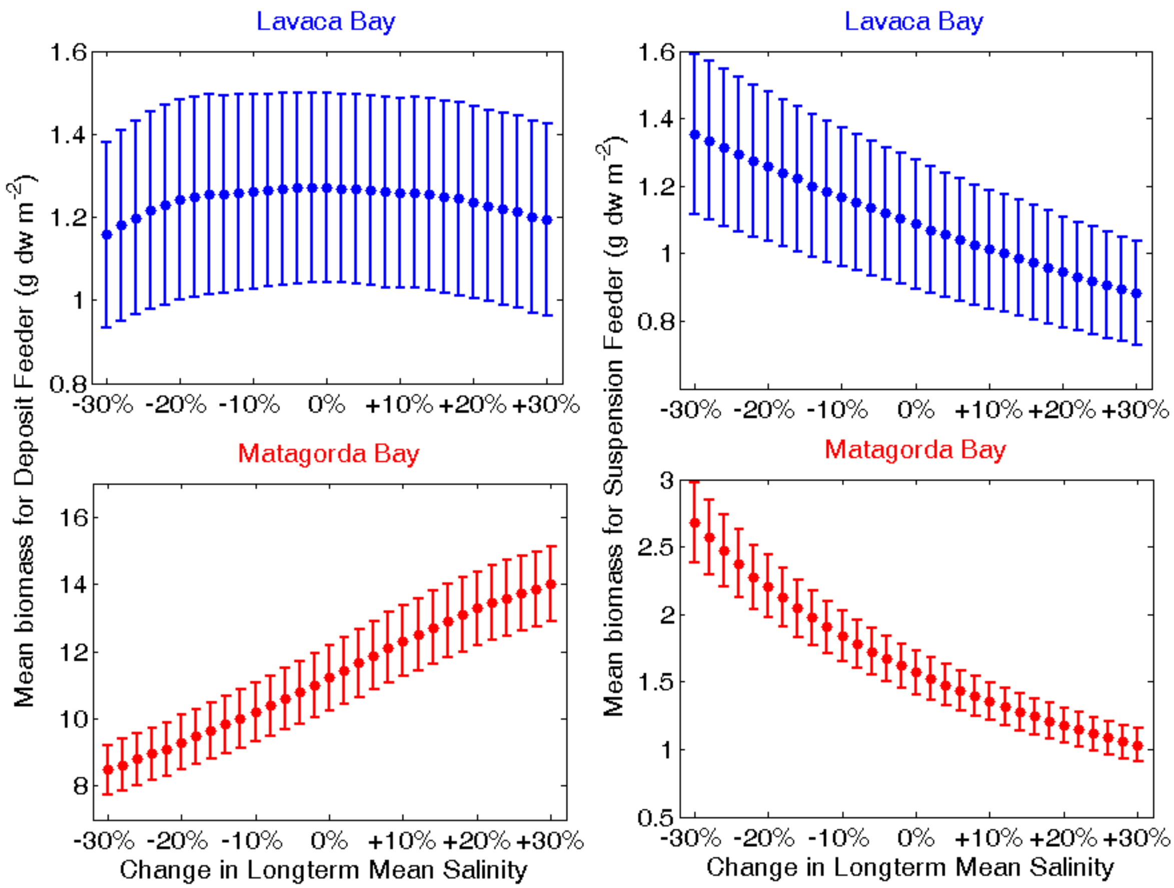


Figure 21. Mean total biomass (solid circles) based on changes (-30 to 30%) in salinity and nutrients for deposit and suspension feeder biomass in Lavaca and Matagorda Bays.

NOTE: In this figure, a simulation under x% of salinity change was conducted for the period of 1988-2005, and simulation results (biomass) were averaged (solid circles) over the entire simulation period, and plotted with error bars (solid lines). The error bars represent the standard error (standard deviation divided by square-rooted number of samples). The number of samples means the number of simulated data points during 1988-2005, which is 69 data points for Lavaca and 72 for Matagorda Bay, respectively. The long-term mean salinity is 15.1 for Lavaca Bay and 24.1 for Matagorda Bay, respectively (see values in the middle of X-axis), and these values represent long-term mean salinity with 0% change. Actual salinity values ranging from -30 to 30% were calculated from the long-term mean salinity values. Note that labels for the X-axis represent salinity change and corresponding changes in nutrients are not shown in the axis labels but were considered in the model simulations.

the trend of change in deposit feeders (Figure 22b). Thus, reducing freshwater inflow from the river and adjacent watersheds may cause the bay communities near and away from the river inflow to respond in different ways. The Lavaca Bay benthic community appears to be harmed by reduced freshwater inflow (and increased salinities) by decreasing in biomass, whereas, the macrobenthos in Matagorda Bay benthos appear to benefit in biomass increase by reduced freshwater inflow (and increased salinities). This effect is probably due to the benthic community of Matagorda Bay containing more salt tolerant species than Lavaca Bay. In EAMB, the region south of the Tripod would behave as predicted for the Matagorda Bay simulations, but the region between the Tripod and the Delta would behave as predicted by the Lavaca Bay simulations because of the differences in long-term salinity average and community composition.

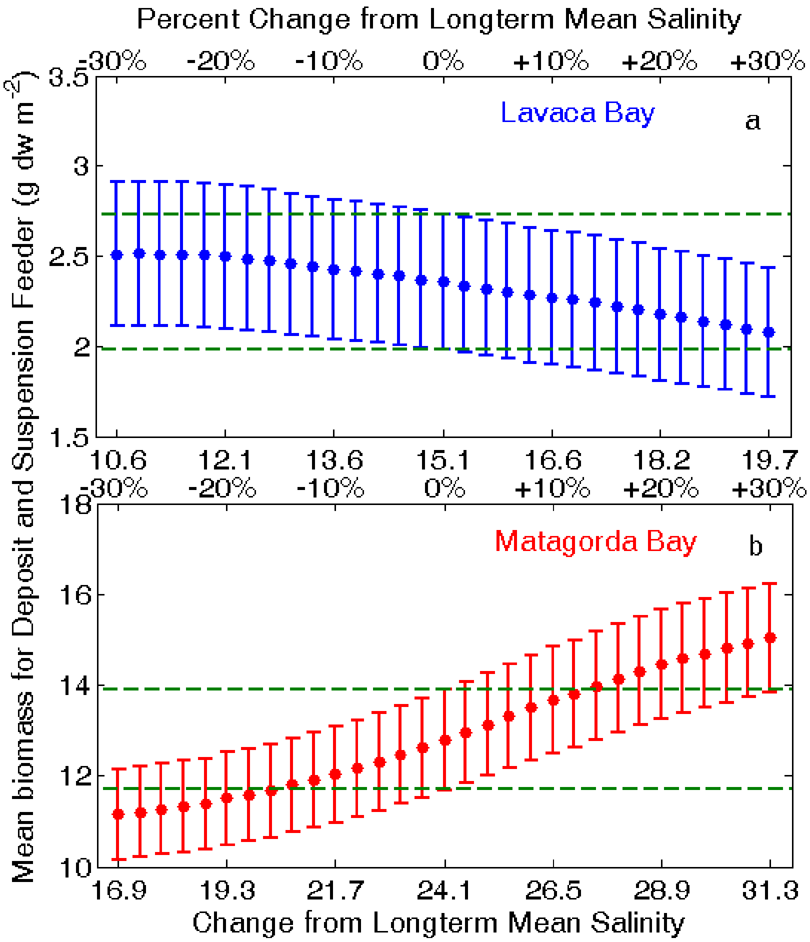


Figure 22. Mean total biomass (solid circles) based on changes (-30 to 30%) in salinity and nutrients for deposit and suspension feeder biomass in Lavaca and Matagorda Bays.

NOTE: In this figure, a simulation under x% of salinity change was conducted for the period of 1988-2005, and simulation results (biomass) were averaged (solid circles) over the entire simulation period, and plotted with error bars (solid lines). The error bars represent the standard error (standard deviation divided by square-rooted number of samples). The number of samples means the number of simulated data points during 1988-2005, which is 69 data points for Lavaca and 72 for Matagorda Bay, respectively. The long-term mean salinity is 15.1 for Lavaca Bay and 24.1 for Matagorda Bay, respectively (see values in the middle of X-axis), and these values represent long-term mean salinity with 0% change. Actual salinity values ranging from -30 to 30% were calculated from the long-term mean salinity values. Note that labels for X-axis represent salinity in psu and corresponding changes in nutrients are not shown here but were considered in the model simulations.

2.4.4 Benthic Results

Integrating the results of the three benthic studies allows an assessment of the potential for changes in benthic condition that result from changes in salinity. The analysis of long-term benthic community structure data reveals strong year-to-year variability in benthic biomass and freshwater inflow, and indicates there has been a general decline in long-term biomass over the study period. These data also show strong spatial gradients of benthic biomass, productivity, community structure, and diversity related to salinity gradients. Long-term salinity values indicate two clear salinity/community zones exist: 1) a brackish and more freshwater-influenced zone (12-19 ppt) including Lavaca Bay stations A and B and Matagorda Bay station F, and 2) a marine-influenced zone (22-27 ppt) that includes Matagorda Bay stations C, D, and E (Table 5). The characterization of benthic habitat variability indicates that conclusions based on the long-term stations generally represent the soft-bottom bay sediments throughout the entire study area. Results of the benthic productivity modeling study also show that benthic productivity is related to salinity. In particular, increases in freshwater inflow lead to greater community and functional diversity, while reduced inflow results in reduced suspension-feeder productivity and increased deposit-feeder productivity in both Lavaca and Matagorda Bay.

Table 5. Long-term salinity. Mean salinity (ppt, ± 1 std. dev.) for April 1993-July 2000, and July 2004-October 2007 during benthic sampling trips.

Zone	Station	Salinity (ppt)	± 1 Std. Dev.
Brackish	A	12.3	9.0
Brackish	B	15.7	9.2
Marine	C	22.0	7.9
Marine	D	26.6	4.6
Marine	E	24.0	5.9
Brackish	F	18.6	8.4

The effects of reduced freshwater inflow (and concomitant increases in salinity) have important management implications for Matagorda Bay. Change in benthic community structure and diversity occurs when salinities change from approximately 18 to 22 ppt (compare Figs. 18 and 19 with Table 5) because that is the break point between the brackish and marine zones for all variables. Thus, change in structure occurs with roughly an 18% change in salinity. Change in biomass and benthic productivity occurs for both trophic groups in Matagorda Bay when the error bar of the long-term average salinity (24 ppt) no longer overlaps with the error bar of 29 ppt, roughly a 20% increase in salinity (Figure 22b). If inflow is reduced and salinity is increased between 18% and 20% the brackish communities take on characteristics of downstream marine communities. This effect is likely a result of the benthic community acclimating to the elevated salinity by the dominance of more salt tolerant species populating the area. It is likely that freshwater inflow plays an important role in maintaining the observed character of estuarine productivity through the combined effects of the frequency, duration, timing, and magnitude of inflow, particularly during droughts or low-flow periods.

2.5 MBHE Bio-statistical Data Analysis and Modeling

The overall objective of the MBHE bio-statistics work is to infer cause-and-effect relations between the populations of selected species in Matagorda Bay and the external controlling factors, one of which is freshwater inflow, by a direct analysis of historical data from the system. While the primary purpose of the bio-statistical analyses are to quantify potential effects of the LSWP and to serve as a tool to help manage the bay system, some of the results of the bio-statistical analyses were used in the formulation of inflow criteria summarized in this section.

The process of evaluating the statistical relationships between organism abundance and significant driving variables requires development and characterization of several parameters. These parameters include those representing the biological abundance of key organisms within Matagorda Bay, various depictions of freshwater inflows contributing to Matagorda Bay, and variables other than flow (such as temperature or commercial harvest) that could affect abundance and whose inclusion in the analysis could help isolate the influence of inflow on abundance. With the exception of oysters, the species addressed here migrate between the bay and the Gulf of Mexico at various stages of their life cycles and their abundance is affected not only by conditions within the bay, but by the larger population in the Gulf and conditions in that environment. The effect of these additional sources of variation in combination with the intrinsic variability in the abundance data themselves is the scatter about the regression line on inflow, i.e., the residual variation in the data that is "unexplained" by inflow. This residual variation can be considerable; so large that some analyses failed to yield a statistically discernible variation on inflow. While the analysis considered various means of quantifying the different variables, methods of data aggregation, and alternative statistical models with the objective of reducing conceptual sources of variance, the fact remains that the data themselves are subject to many natural sources of variance that are extraneous to the single variable of inflow.

2.5.1 Biological Parameters

As noted in the 2006 Bio-Statistics Progress Report (MBHE 2006d), the TPWD Coastal Fisheries Database has been used as the source of the abundance data for Matagorda Bay in this project. All four gear types used by TPWD in their sampling program — otter trawl, bag seine, gill net (total mesh), and oyster dredge — were analyzed in the overall MBHE bio-statistical effort. Each of these except gill net was converted to organism density on an aerial or volumetric basis, employing the gear dimensions and sampling protocols of TPWD. Although all gear types were considered in the overall effort, for use in inflow-criteria work, only otter trawl data were employed, because they better represent the populations in the open-bay waters.

The fundamental temporal measure of abundance in this effort is the “organism-year” mean. For the purposes of this study, this is defined as the average abundance over the period of 12 months that best captures an annual cycle of a given organism’s activity within the bay. For species that have a single “grow-out” period of less than a year, such as shrimp, the organism-year mean will represent that year’s “crop.” For longer-lived species, the organism year is equivalent to the fisheries concept of year class. The key species included in the bio-statistical analysis and the corresponding organism years are given in Table 6.

Table 6. Selected representative species and organism years.

Species	*Latin name*	Organism year
Brown Shrimp	*Farfantepenaeus aztecus*	Mar – Feb
White Shrimp	*Litopenaeus setiferus*	Jun – May
Blue Crab	*Callinectes sapidus*	Jan – Dec
Eastern Oyster	*Crassostrea virginica*	Jan – Dec
Atlantic Croaker	*Micropogonias undulatus*	Oct – Sept
Gulf Menhaden	*Brevoortia patronus*	Nov – Oct
Red Drum	*Sciaenops ocellatus*	Sept – Aug
Spotted Seatrout	*Cynoscion nebulosus*	Feb – Jan

For the purposes of the development of inflow criteria, the biological analyses have focused specifically upon "whole bay" average abundances, in contrast to regional averages in which the data are spatially disaggregated into areas of geographic significance, which was carried out in the overall bio-statistical analyses (see MBHE 2006d). Whole bay average abundance measures the entirety of the population of the species in the bay, and therefore the relation between inflow and whole-bay abundance is indicative of the total effect of inflow on the presence (or absence) of the species in the bay. Moreover, because the whole-bay abundance is not subject to variation due to migration of the species population from one area of the bay to another (in contrast to the abundance in a specific sub-region), this source of variance in the data is automatically eliminated and the statistical relations better exhibit the influence of inflows on the total population of each organism in the bay.

2.5.2 Hydrologic Parameters

For freshwater inflow-criteria development, the hydrology was limited to the variable of Colorado River inflowing to Matagorda Bay (COLMB), defined to be the totality of those flows from the Colorado River catchment contributing flow to Matagorda Bay. (additional geographical accumulation of inflows is detailed in MBHE 2006d). Three historical periods of flow data were of particular concern in this work and its use in inflow criteria development: the gaged period of record at Bay City (1949-2005), the period of record encompassed by the TPWD Coastal Fisheries data base (1977-2006), and the period since the implementation of the Colorado River diversion project of the USACE (1993-present).

Inflow is a complex time-varying signal, for which the basic data (United States Geological Survey [USGS] gage records, National Weather Service [NWS] precipitation data, etc.) have a time resolution generally limited to one day. The hydrographic structure of the bay and *a fortiori* the response of organisms to inflow are time-integrators and generally respond to the longer period variations in inflow. An early challenge in the bio-statistical analysis was to mathematically process the detailed time signal of flow to extract measures of inflow more indicative of the responses of the bay, in particular to better reflect how the major organisms in the bay respond to inflow. The underlying conceptual model is that the presence of the study species in the bay is keyed to the typical seasonal variation of inflow. In Texas, this variation includes pulses of flow, or "freshets," especially in the spring and fall seasons, which are composed of superposed storm hydrographs. The mathematical characterization of a seasonal pulse or "freshet" was developed, namely a surge of inflow that occurs over a period of weeks to months.

Temporally, in the development of inflow criteria, flow was evaluated utilizing three measures:

- annual;
- three-month approximate freshet (three calendar months); and
- freshet from objective methodology.

Annual flows are the more conventional measure and provide a convenient index for long-term variation in hydroclimatology (notably extended "wet" and "dry" periods), as well as providing a standard by which to evaluate the success of the other measures. (for biostatistical relations, the 12-month averaging period depends upon the organism year, see Table 6). The Three-Month Freshet analysis is based on the maximum three calendar-months cumulative spring and fall flow amount, and is essentially the method used to study seasonal inflow hydroclimatology in the two National Estuary Programs in Texas (viz., Galveston Bay and the Coastal Bend Bays). It was developed as a convenient and approximate means of evaluating seasonal inflow surges to Matagorda Bay using monthly flow data (referred to as "preliminary" in MBHE 2006d), with the spring period defined as having an onset occurring between January and May and the fall period defined as having an onset occurring between August and October.

The objective freshet methodology is a mathematical method for isolating seasonal pulses of flow in the daily inflow record, yielding three freshet parameters of onset, magnitude, and duration, which together delineate the seasonal freshets in a given year. The magnitude of a freshet is simply the volume of flow contributed by the pulse of water, while the duration is the time (e.g., number of days) the freshet lasts. Briefly, the objective freshet method deals with two low-pass filtered time signals of inflow, one with a 45-day (1.5-month) sliding average of the daily record, the other a six-month sliding average. The time change of the logarithm of flow (i.e., the time change as a proportion of the flow magnitude) is tracked daily for the first of these filtered time series. The beginning of a freshet is identified by a positive spike in time change that exceeds a threshold dependent upon the corresponding six-month mean value, and the end of the freshet by a negative spike relative to a similar threshold. There are no preset prescriptions on the duration, seasonal onset, or magnitude of freshets so defined, but it emerges that there are generally 2-4 freshets identified in the data record per year, predominantly in the spring and fall seasons.

The objective freshet methodology occasionally determines that a freshet did not occur during a season when one would ordinarily be expected, i.e. the flow time series did not exhibit the mathematical properties of a freshet pulse. This is not surprising, as there are indeed years in which the seasonal pulse of flow in the spring or the fall simply does not occur. In some of the statistical analyses, these non-occurrences were treated as zero events. However, for the analyses underlying the inflow criteria, it is desirable to have a measure of inflow for every year, even if that inflow does not present itself as an identifiable pulse. When a freshet (in this mathematical sense) does not occur, a substitution methodology is employed, as reported in MBHE 2006d, the resulting freshet history being designated "3-sub."

An important point in the time history of inflows is the 1991-92 construction of the Colorado River diversion, part of the USACE Mouth of the Colorado project. This included a plug dam in Parkers Cut; dredging of the bypass channel from the old river-Gulf channel to the GIWW east of the lock structures; installation of the plug dam in the old river-Gulf channel downstream from the GIWW;

and installation of the jetties and dredging of the Colorado-Gulf channel, as well as the dredging of a new channel for the Colorado into the EAMB. Some of these, especially the closures of Parkers Cut and of the shunt channel to the Gulf, have the potential for affecting the presence of diadromous species in Matagorda Bay.

2.5.3 Bio-statistics Results

Using the aforementioned combinations of input data, multivariate regressions for each organism abundance (as the dependent variable) with both linear and non-linear regression forms were generated and analyzed to assess which, if any, yielded statistically valid and meaningful relations. These analyses were performed for different organisms, gears, and methods of estimating abundance, geographical regions, and parameterizations of inflows. Separate analyses were carried out for post-diversion data, and for biological data extending back to 1977. For some of the species, there is evidence that the statistical behavior fundamentally changed at the time of the diversion project, which must be borne in mind when pre-diversion data are considered. More detail on these aspects of the bio-statistical work is given in MBHE 2006d.

As noted earlier, there exists great residual variation of abundance data about the statistical relations solely based on inflow. As far as the key species addressed in the bio-statistical effort are concerned,

1) the annual-mean abundances are highly variable even when a variation with flow is taken into account due to a combination of intrinsic fluctuation in the field data measuring abundance and the effects of variables other than inflow; and
2) no reduction of inflow levels in the historical record has resulted in elimination of any of these species from the bay (because there are no zero values of annual-mean abundance in the data record), nor has it precluded the re-establishment of its population after that population has suffered a reduction (because they continue to exist at more-or-less historical levels).

Therefore, the data record does not admit to a level of inflow that is, in some sense, catastrophic for any one of these species, and which, therefore, would have to be exceeded at all times. Over history, the populations have risen and fallen. Moreover, progressing west along the Texas coast from estuaries of high inflow to low inflow, there is a change in the total and relative abundance of these and other species, in which it is a reasonable presumption that the diminishing inflow plays a role. We cannot therefore extract from the bio-statistical observations a fixed value of inflow representing a threshold below which Matagorda Bay will lose some aspects of its ecology. Rather, the inflows necessary to maintain the characteristics of Matagorda Bay and that distinguish it from, say, San Antonio or Galveston Bay, are quantified by a statistical distribution, and any inflow criteria would also be statistical. Our purpose in formulating such a criterion is to identify specific flow quantities and an associated frequency of occurrence (informed by their historical occurrence over the hydrological period of record, 1949-2005), potentially capable of influence by anthropogenic factors, that can function as a convenient index to preserving some overall statistical variation of the abundance of organisms.

As noted above, the high variability about the statistical regressions developed in the biostatistics work make it difficult to extract specific quantitative inflow criteria that exhibit any assurance of meeting the regressed values of abundance a majority of the time. But other useful conclusions can be drawn from the available data upon which the regression relations were developed, notably the importance of freshet flows to abundance and which season is most important to a given organism. In general, significantly improved explained variance was achieved using seasonal freshet parameters, as opposed to say, annual flow. The strongest regressions were found for white shrimp (versus fall freshets) and Atlantic croaker (versus spring freshets). It is assumed that if these flows are protected then these and any other organisms that respond to these freshet flows would be protected as well.

2.6 Nutrient and Chlorophyll-*a* Modeling

While the relation between inflows and ecological health and productivity of the bay system is complex, there is little doubt that it involves both habitat (e.g., a suitable salinity range and physical habitat conditions for various organisms) and food supply introduced through inflows. When there is a shortage of food, organism growth tends to be reduced and health can be affected. Without addressing the situation of excess food supply that is not a part of this flow needs analysis, when more food is available to the bay system, overall productivity tends to be enhanced (Odum 1971). While a general statement of a relation between food supply and productivity is not controversial, going to a specific quantification is complex and requires addressing several key aspects of the system, namely

- The relation between inflows and food supply has been addressed in the MBHE effort over three years and this has built on a substantial amount of previous work by the TWDB, TPWD, Texas Commission on Environmental Quality (TCEQ), LCRA and various academic institutions. The principal findings and conclusions summarized in the effort (MBHE 2007c) dealing with food supply include:
- A finding from the literature that phytoplankton primary productivity is likely to be a very important component of the base of the estuarine food web in the Matagorda Bay system. The chlorophyll-*a* concentration measured in the bay is a widely accepted measure of phytoplankton primary productivity.
- A conclusion from both the relevant literature and available field data that inflows carrying nutrients, primarily inorganic N supply, is the dominant component in regulating the level of phytoplankton primary productivity. Inorganic N is also released from the sediment, particularly during dry periods, and this process acts to modulate phytoplankton primary productivity.
- Organic matter carried on inflows is also important to the base of the food web. Because the mechanisms involved in the transport of this organic matter are similar to those of inorganic nitrogen, they are considered in combination. Organic N contributed in inflows is a source to the sediment that supplies inorganic N during dry periods. Other components of the bay food supply such as seagrass, benthic algae and tidal wetland are recognized as smaller contributors and not explicitly quantified.

The MBHE team developed and calibrated a model that provides a simplified representation of the relation between nutrients carried by inflows and the amount of primary production, as represented by phytoplankton chlorophyll-*a* concentrations. The following sections describe the model and its application to the problem of estimating specifically how much inflow is needed to provide bay food (as described in this section) sufficient to maintain ecological health and productivity.

2.6.1 Nutrient and Chlorophyll-a Model Description

The United States Environmental Protection Agency's (USEPA) Water quality Analysis Simulation Program (WASP) 7.1 was used to develop the nutrient-primary productivity model. WASP7.1 is made available by the USEPA and is in the public domain. The model has undergone continual development since the first version appeared in the early 1980s, and it has been applied to many rivers, lakes, reservoirs, estuaries and bays. WASP7.1 is a dynamic compartment-modeling program for aquatic systems, including both the water column and the underlying benthos, and can be used to investigate 1-, 2-, and 3-dimensional systems and a variety of constituent types. The time-varying processes of advection, dispersion, point and diffuse mass loading and boundary exchange are represented in the model.

The following state variables were modeled:

- ammonia nitrogen (NH_3-N);
- nitrate nitrogen (NO_3-N);
- organic nitrogen (OrgN);
- orthophosphate (OP) or soluble reactive phosphorus (SRP);
- organic phosphorus (OrgP);
- phytoplankton;
- dissolved oxygen (DO);
- carbonaceous biochemical oxygen demand (CBOD);
- total suspended solids (TSS); and
- salinity.

The hydrodynamic model RMA2 developed for the MBHE provided the hydrodynamic data to drive the nutrient-primary productivity model. The WASP model provides a simplified representation of the relation between nutrients carried by inflows as well as those released from the sediment, and the amount of primary production, as represented by phytoplankton chlorophyll-*a* concentrations. Details of the literature, data, calibration, and accuracy checks are provided in Bay Food Supply Final Report (MBHE 2007c). Figure 23 shows a model diagram that illustrates the key links between the variables and processes involved.

The Matagorda Bay system was divided into 12 segments as shown on Figure 24. The EAMB, our primary area of interest, encompassed five segments. Since the focus was on EAMB, Lavaca Bay, Carancahua Bay, and Tres Palacios Bay were each represented by only one segment and the lower main bay was represented by four segments.

The bays receive loads of nutrients (nitrogen and phosphorus as well as organic matter) from the gaged and ungaged watersheds surrounding the bays. For all parameters except suspended solids, the daily average flows from the gaged and the ungaged areas were multiplied by constant concentrations to yield loads. The solids loads were calculated based on linear regression relationship developed between flow and concentration, described in MBHE 2006c. Because

WASP7.1 has only a limited capability for benthic simulation, a sediment flux model provided by EPA was used to estimate the sediment fluxes of ammonia and phosphorus.

Model calibration was performed for the period from July 1995 to December 2002; this time period encompassed both low flow and high flow periods. RMA2 hydrodynamic results were used to drive the WASP7.1 models. Field observations used for comparing with model results were either from the TCEQ Surface Water Quality Monitoring (SWQM) database, LCRA, or Harte Research Institute for Gulf of Mexico Studies (HRI).

2.6.2 Nutrient and Chlorophyll-a Model Discussion

The model represents the fundamental relationship between nutrient supply and primary productivity. It does so with a simplified version of the true system (e.g., a single phytoplankton group is simulated, rather than the many that actually compete) that represents the correct direction of response to changes in the limiting nutrient and is close to the average magnitude of the changes demonstrated in the data. It provides a tool that can be used to gage the primary productivity response of the system to changes in inflows.

The model is a representation of the system that currently exists and does not represent ecosystem changes that might occur in response to major changes in inflows. For example, the Laguna Madre is a valued and productive ecosystem which receives much lower levels of inflows than the EAMB. To do so, it has many differences from Matagorda Bay. In theory, similar changes could occur in Matagorda Bay, but at significant cost to the existing resources. This is not a desired outcome and the model is not capable of simulating these types of changes. Because of the nature of the model representing the existing system, the decision was made to apply this model to the problem of determining the average inflow needed to maintain the existing system and to not address extreme drought conditions when ecosystem adaptations could be expected to play a role.

The EAMB model is used in this analysis to estimate the long-term average inflow volume that will support the level of phytoplankton primary productivity that is characteristic of the EAMB since the diversion. In conjunction with an analysis of inflow volume, the model has also been used to explore and document the importance of maintaining high flow pulses, which contribute significantly to the delivery of nutrients to the bay system. In addition, the model is used in a supporting role to determine an inflow level needed to avoid extremely low levels of chlorophyll-*a*.

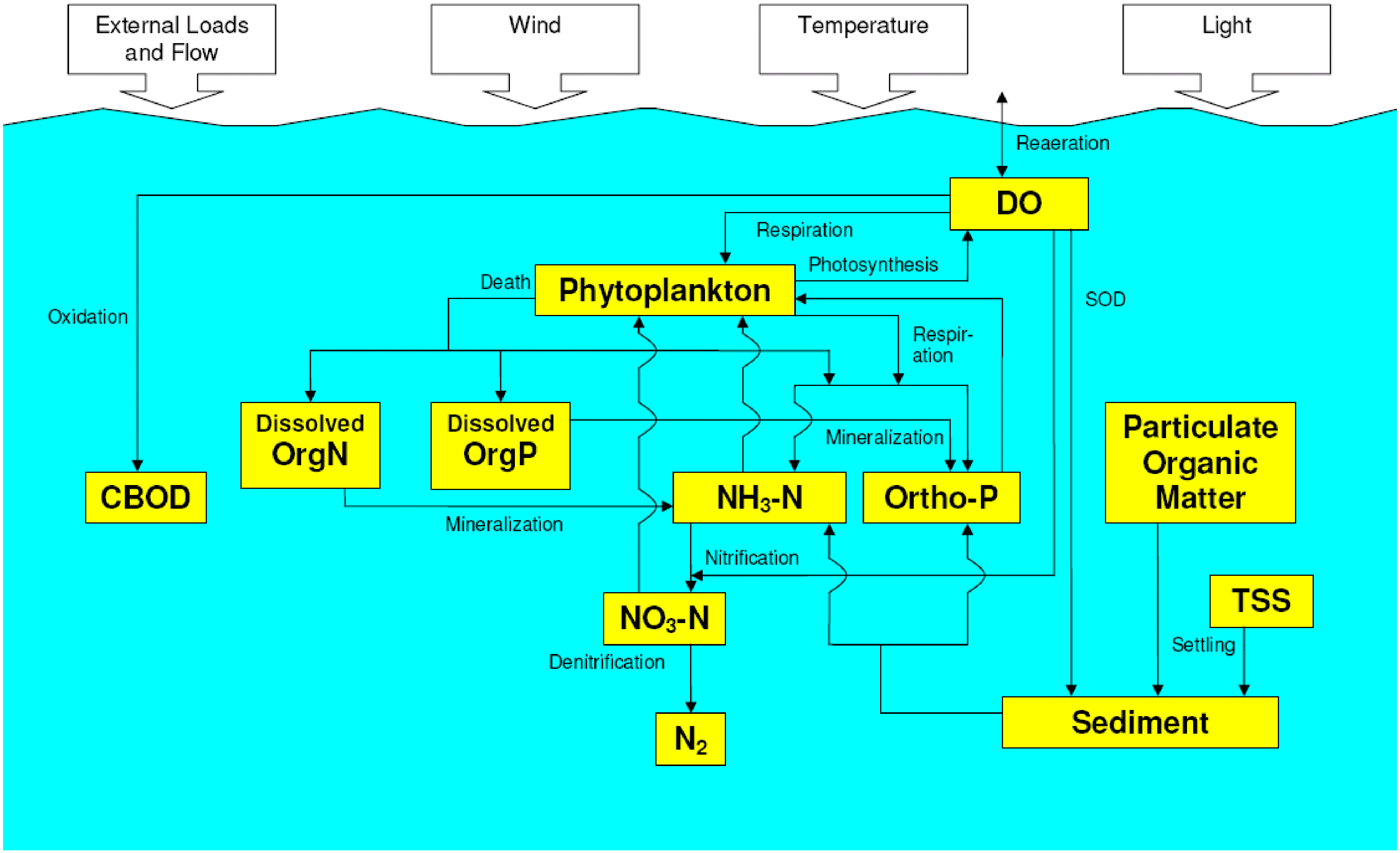


Figure 23. Model schematic for nutrient modeling of Matagorda Bay (WASP 7.1).

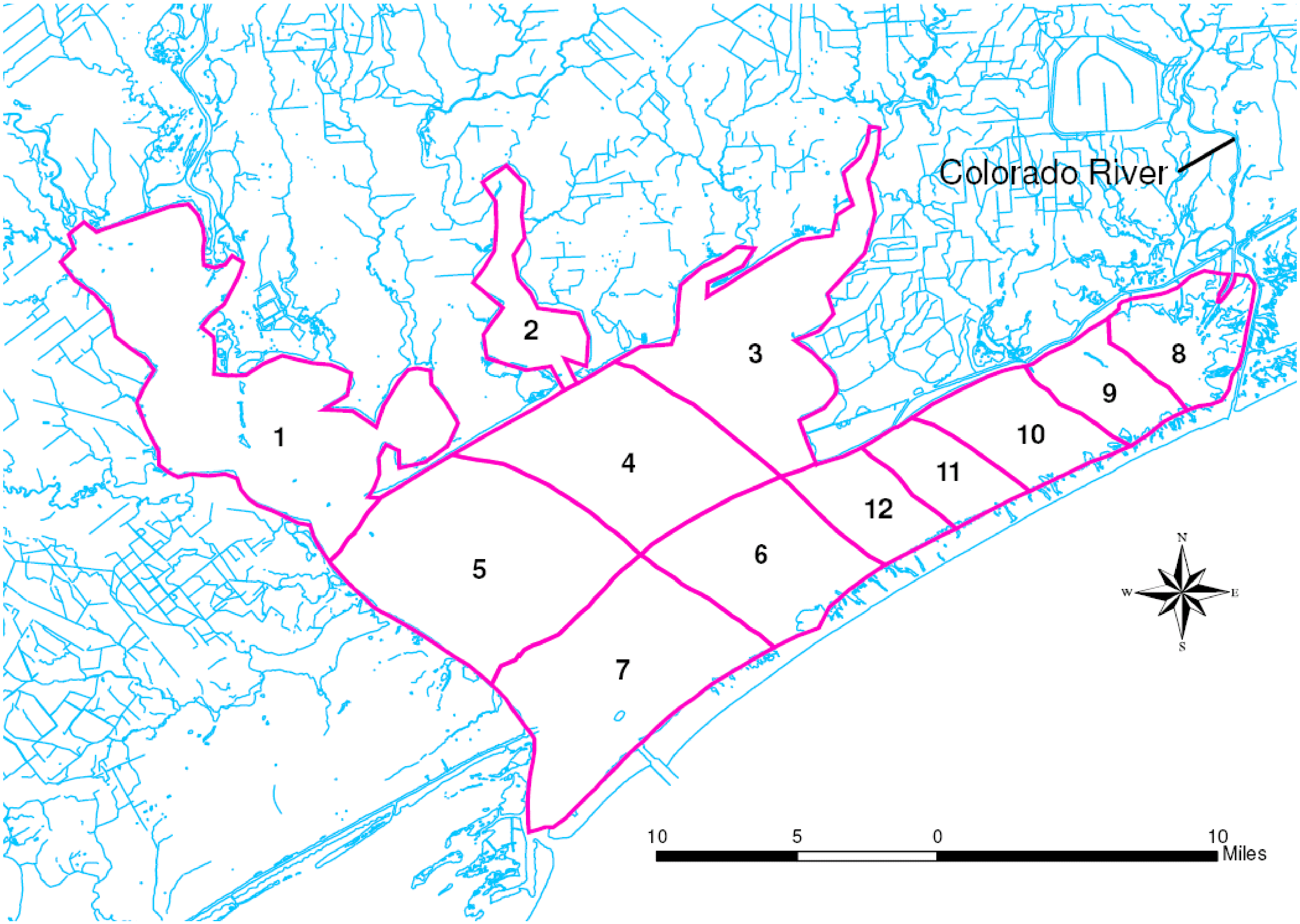


Figure 24. Segmentation of Matagorda Bay Model.

2.6.3 Chlorophyll-a Results

To address the flows needed on a long-term average basis, the first aspect that must be considered is the historical record of chlorophyll-*a* and inflow. The historical record in the EAMB begins in March 1979 and extends through August 2006 in this analysis. Excluding seven questionable values that were reported as "<1" ″ µg/L, there are 126 chlorophyll-*a* observations available. In the post diversion period (10/92 to 8/06), there are 82 observations with a median level of 7.01 ″ µg/L and an average of 8.24 ″ µg/L. These observations for the EAMB reflect a wide range of conditions, with both high and low flows represented. They can thus be considered to represent a snapshot of "normal" conditions.

The values can be used for management purposes, but the limitations of any snapshot of data need to be understood and accommodated. These data are a combination of observations made by three different groups (TCEQ, LCRA and HRI) over 14 years in different conditions and locations within the EAMB. In detail, the 82 post-diversion data includes:

Number of Data Points				**Min**	**Median**	**Mean**	**Max**	**Range**	**Stdev**
TCEQ	LCRA	HRI	Total						
11	18	53	82	1.61	7.01	8.24	33.2	31.59	5.15

Each individual observation carries with it a measure of variation. For example, the TCEQ Quality Assurance Project Plan shell, http://www.tceq.state.tx.us/compliance/monitoring/crp/qa/QAPP-0809.html , specifies that replicate analyses are within +/- 20%. In an extensive comparison of data between HRI and LCRA (see MBHE 2006c, Appendix A), the average difference in 14 split chlorophyll-*a* samples collected over the study area was 1.3 ″ µg/L or 16%. In the analyses that follows, it will be assumed that ±1.3 ″ µg/L is an appropriate expected range to apply to the historical snapshot of data.

The model and historical data were used in different ways to determine what flow levels and what pattern of flows would be needed to best maintain the historical levels of EAMB primary productivity that have been observed. The following sections describe the modeling and data analyses produced to support an estimate of the level and pattern of flows required.

Modeling Approaches. Conditions from 1996 were employed and the modeling was performed using RMA2 hydrodynamics. This year was selected because relative to the rest of the record, the river and local watershed flows were both low and stable. With that condition, changes in river loads have the most immediate effect on chlorophyll-*a* levels in the EAMB.

The WASP model (which was calibrated using data from 1995-2002; see MBHE 2007c) was first employed with different levels of steady nutrient loads that correspond to steady inflows. Table 7 summarizes the results for the 12-month period. The inflows to the EAMB averaged 710 cfs (514,000 ac-ft/yr) during 1996 with the predicted chlorophyll-*a* concentration averaging 3.27 µg/L. (For details of the model and procedures, refer to the Bay Food Supply Final Report [MBHE 2007c].) The loads input to the model were then increased corresponding to the indicated river flows (i.e., 1000 cfs, 2000 cfs, etc.; see Table 7). The actual flows into the EAMB that would correspond to the changes in river flows are shown as well. For each steady inflow condition, the nutrients, organic matter, and solids loads are added on a continuous basis. Because all of the flow levels considered here are not relatively high (compared to "true" high flow or storm events historically seen on the river), no changes were made in the 1996 (i.e., calibrated) sediment flux rates for these predictions. The average chlorophyll-*a* concentrations for each steady inflow rate are presented for each model segment and the EAMB overall. From these runs, the inflows needed to meet the historical median and average chlorophyll-*a* levels were determined by interpolation. The corresponding median and average flows to EAMB are listed in Table 8, excluding the very small contribution from local watershed 15010. The calculations are done for the expected range as well.

Table 7. 1996 model results of chlorophyll-a.

1996 MODEL RESULTS OF CHLOROPHYLL-*a*							
Scenario	Chlorophyll-a (" µg/L)						EAMB
	Seg8	Seg9	Seg10	Seg11	Seg12	EAMB	flow
						Average	(cfs)
Calibration	5.16	4.08	3.08	2.28	1.73	3.27	710
Steady CR flow (1000 cfs)	6.12	4.47	3.25	2.37	1.77	3.60	783
Steady CR flow (2000 cfs)	12.17	8.24	5.56	3.76	2.58	6.46	1,622
Steady CR flow (2500 cfs)	15.39	10.24	6.79	4.50	3.01	7.99	2,062
Steady CR flow (3000 cfs)	18.65	12.29	8.07	5.27	3.45	9.55	2,516
Pulse [1] (average 1000 cfs CR flow)	7.27	5.09	3.56	2.52	1.84	4.06	835
[1] *See text for description of pulses.*							

Table 8. Inflows needed to meet historical chlorophyll-a levels.

	To meet median chlorophyll-*a*	**To meet average chlorophyll-*a***
Flow needed for model to meet Post-Div Chl *a*	1,289,000 ac-ft	1,547,000 ac-ft
Flow needed to match Chl *a* at lower limit of expected range	1,011,000 ac-ft	1,274,000 ac-ft
Flow needed to match Chl *a* at upper limit of expected range	1,560,000 ac-ft	1,821,000 ac-ft

The average flow from the chlorophyll-*a* simulation is lower than the actual average flow to the EAMB during the 1995-2002 calibration period of 1,940,000 ac-ft, whereas the flow needed to achieve the median chlorophyll-*a* concentration is higher than the actual median flow during the calibration period of 838,000 ac-ft. The inflows to the EAMB during the period 1977-2003, which correspond fairly closely to the period of the historical record of chlorophyll-*a*, are substantially lower — a median of 527,000 ac-ft and an average of 1,165,000 ac-ft.

Flow Variability Analysis. One aspect that is clear from the historical record is that inflows tend not to be steady, but rather occur in pulses or freshets. This analysis addresses the historical loads of nutrients and solids to quantify the type of variability that has been a desirable component of the historical condition and that should be maintained in the future condition.

Table 9 presents the loads of inorganic-N (sum of ammonia and nitrite-nitrate-N), an important part of the nutrient needs for primary productivity, expressed on both a daily and monthly basis, broken out by percentile. The largest loads are conveyed in the highest percentile values, as would be expected. Figure 25 illustrates how the 50th percentile inorganic-N loads and below account for only 9.3% of the total daily and 12.4% of the monthly cumulative loads. The bulk of the loads are associated with the high load (and high flow) intervals.

Another important part of the nutrient supply to the system is organic material carried in the water. The concentrations of suspended organic matter tend to increase in large runoff-dominated flows. Figure 30 shows the loads of volatile suspended solids (VSS) by flow percentile. The VSS loads are associated with high flow periods more often than inorganic-N.

The importance of flow spikes was also explored with the model. To do this, the same base condition as used with the steady flow was employed (i.e., "Calibration" in Table 7). The main change was to reduce the base flow nutrient loads to those associated with a flow of only 500 cfs and concentrate the difference in flow into three events of constant higher flow, each two weeks in length, starting on May 1, July 1, and September 1. These dates were selected to cover the range in solar insolation during the summer. The nutrient loads that enter the EAMB during these shorter events are higher. With the hydrodynamics of the model reflecting a relatively low inflow period, the higher nutrient loads produce concentrations that take somewhat longer to disperse across the EAMB. Nevertheless, the effects on chlorophyll-*a* appear to be as expected. The bottom row of Table 7 presents the period-long average chlorophyll-*a* concentrations associated with an overall average of 1,000 cfs flow introduced in pulses. One effect of introducing the flow in pulses is to have a slightly higher proportion of the flow enter the EAMB rather than flowing to East Matagorda Bay or to the Gulf of Mexico.

Table 9. Inorganic-N loads to EAMB, 1977-2005.

	Daily Loads (kg/d)				Monthly	% of total
	CR load above GIWW	CR load to EAMB	% of total CR load to EAMB	Load to EAMB (inc 15010)	CR load to EAMB (kg/monthly)	Monthly VR load to EAMB
Average	5,980	3,532		3,754	107,491	
Stdev	13,141	8,570		8,795	163,989	
Percentile						
10%	673	394	0.7%	406	16,492	1.3%
20%	965	563	2.0%	586	22,119	3.0%
30%	1,223	740	3.9%	773	29,310	5.5%
40%	1,526	937	6.3%	987	36,344	8.5%
50%	1,907	1,239	9.3%	1,309	47,050	12.4%
60%	2,563	1,644	13.4%	1,758	63,925	17.4%
70%	3,795	2,428	19.0%	2,600	88,264	24.3%
80%	6,422	4,045	27.9%	4,414	130,347	34.6%
90%	12,820	6,934	42.7%	8,006	266,299	52.2%
100%	161,233	161,233	100.0%	161,298	1,218,023	100.0%

1 This column shows the percentage of total load contributed by daily loads less than or equal to the corresponding CR daily load to EAMB.

2 This column shows the percentage of total load contributed by monthly loads less than or equal to the corresponding CR monthly load to EAMB.

It is clear that maintaining the variability in inflows is important. Simply meeting an average or median inflow goal with uniform values every month would not maintain the long-term average primary productivity because the bulk of the essential nutrients that support the long-term average chlorophyll-*a* level are supplied by the relatively infrequent high flow events that are a critical part of the system variability.

One way to view variability is the coefficient of variation (CV), defined as the standard deviation divided by the average of a data set. This measure of variability as used below does not have a seasonal dimension, and it could be argued that including a seasonal requirement would be desirable. Certainly pulses of flow and nutrients that occur in the spring and early summer will translate into chlorophyll-*a* more rapidly than they would if the same pulse occurred in the winter. No attempt to incorporate a seasonal component is included in this analysis because the timing of larger inflow events is not something that can be affected by LCRA or the LSWP (i.e., high flow events are due to natural storms). The project or future conditions could have some small effect on the magnitude of large inflow events and the CV addresses that dimension.

Figure 27 presents a time series of CV values for the Colorado River monthly flows to the EAMB from 1977-2005. A noticeable dimension of the curve is the increase in CV values after the diversion (post- 1992). This is a result of the larger volume of flow and greater variability of that flow that resulted from diverting the river channel to the bay. The CV values, as shown in Figure 27, are dimensionless.

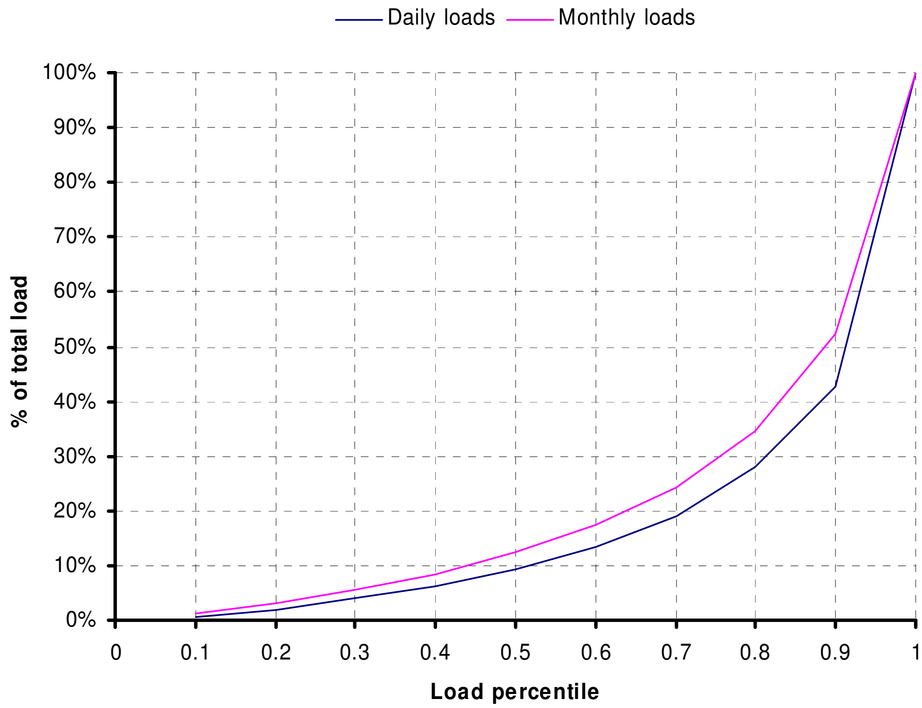


Figure 25. Distribution of Inorganic-N loads to the EAMB.

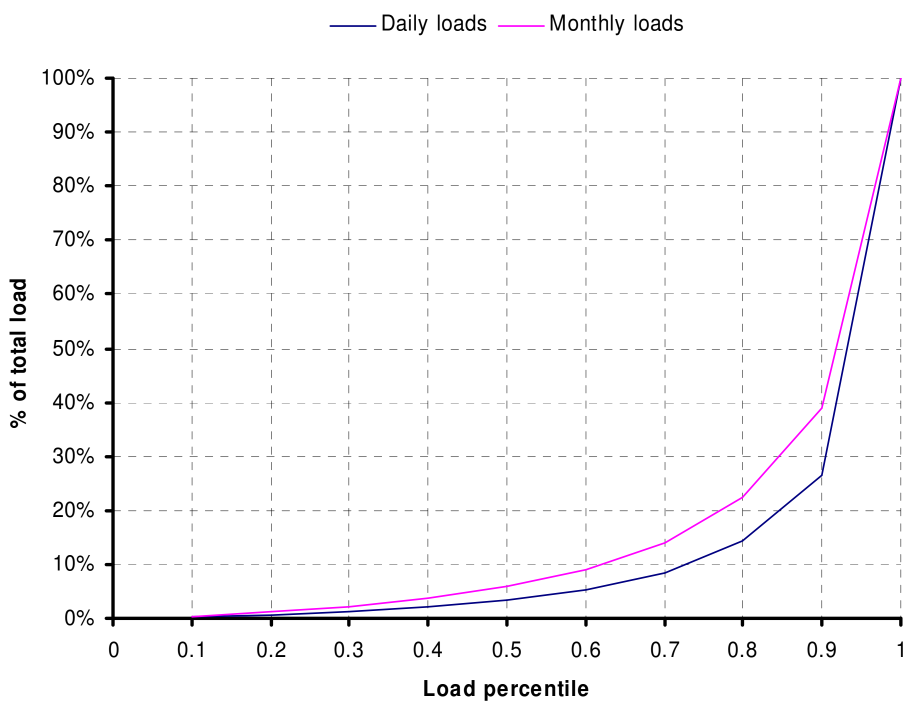


Figure 26. Distribution of VSS loads to the EAMB.

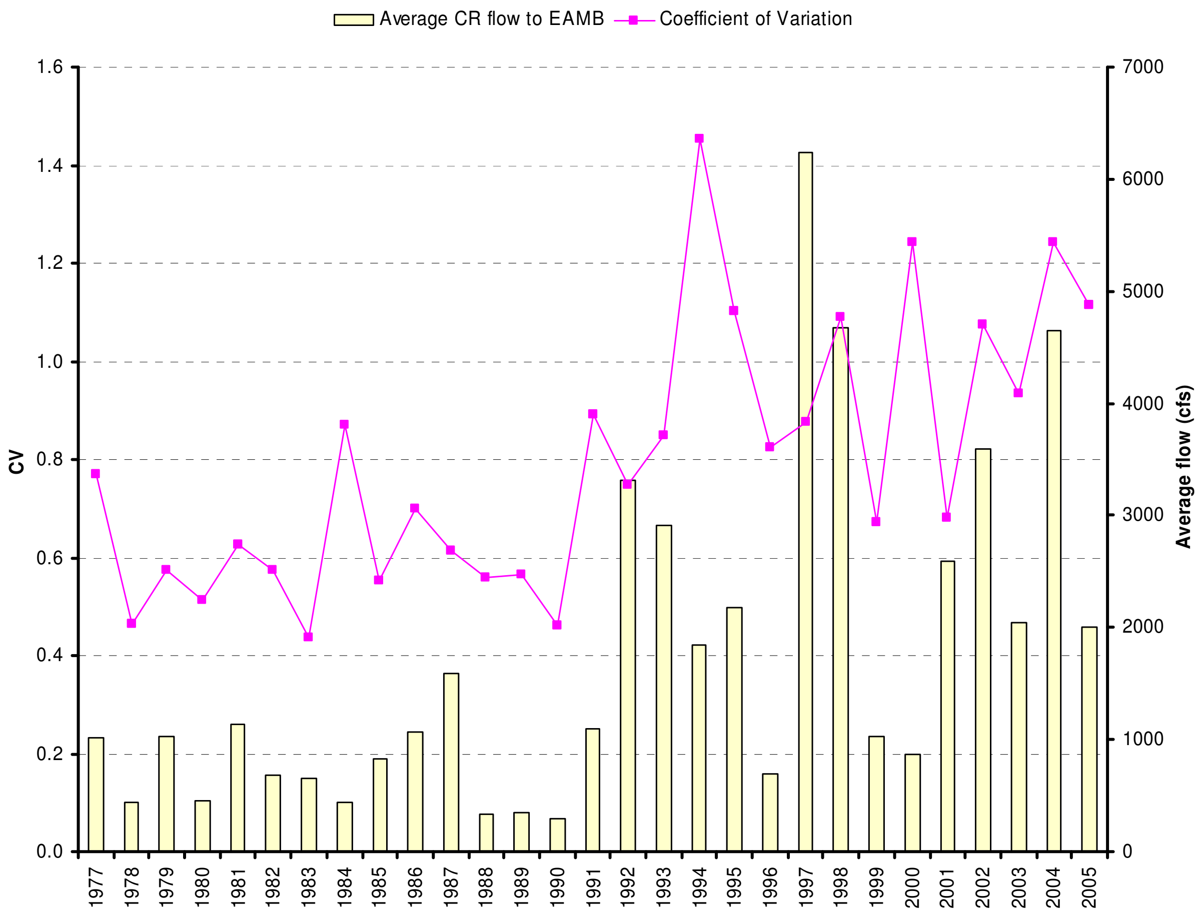


Figure 27. Coefficient of variation of Colorado River flow to the EAMB.

3.0 Freshwater Inflow Criteria Development

Each of the measures of bay health and the attendant models and data analyses that underlie the measures has been employed to provide results which can be used to develop a comprehensive set of inflow criteria, which, when applied to the future inflows from the Colorado River, are intended to protect the health and productivity of the bay. It is acknowledged that these criteria will be imperfect, and the recommended long-term monitoring of bay health and productivity is an integral part of properly managing the bay system. The results of this monitoring should be utilized to revisit the adequacy of the proposed criteria from time to time.

Figure 28 outlines the MBHE Freshwater Inflow Criteria Development process. Select data inputs are shown along with key models (Hydrodynamic/Salinity Model, Habitat Model, Nutrient [WASP] Model, Dermo Condition Index Model, and Benthic Productivity Model). The flowchart is not meant to be all-inclusive as multiple data sources are utilized and many steps are necessary to run each respective model. Results from each measure of bay health are represented by light green trapezoids. MBHE freshwater inflow criteria categories are represented by light blue diamonds. Bay food was the primary measure used in the development of the Long-Term Volume and Variability criteria. Habitat, dermo condition index, and benthos were the primary measures used for the development of MBHE 1-4 criteria, while benthos and dermo condition index were the primary measures used in the development of Threshold criteria. For the MBHE 1-4 and Threshold criteria, inflow volumes were calculated based on salinity to inflow relationships developed from a long-term salinity model simulation.

The general framework for flow distribution of inflow criteria is shown as is the linkage to long-term monitoring throughout select locations in Matagorda Bay. Solid lines and arrows depict direct relationships and the general flow of information while dashed lines describe confirmatory linkages. The following sections will first provide an overview of the freshwater inflow criteria categories followed by detailed descriptions of the components used and methodologies employed for the development of MBHE inflow criteria.

3.1 Freshwater Inflow Criteria Categories

An adequate freshwater inflow regime is essential to maintaining the health and productivity of Matagorda Bay. A regime consists of high, moderate, and low inflow conditions intertwined with variability. When discussing Matagorda Bay, it is important to remember that an inflow regime is driven by many contributors. These contributors include:

1) inflow directly from rivers and tidal streams,
2) coastal watershed runoff from localized precipitation events,
3) irrigation return flows from localized agricultural activities, and
4) tidal exchange with the Gulf of Mexico.

For the development of the inflow criteria presented herein, the focus is placed on inflows being provided via the Colorado River, but within the context of the other contributing factors. We also recognize that flood flows are extremely important to an estuary to provide inputs of sediment, organic matter, and nutrients, while dampening salinities and providing parasite control. However, extreme flood flow events on the Colorado River are largely beyond human control.

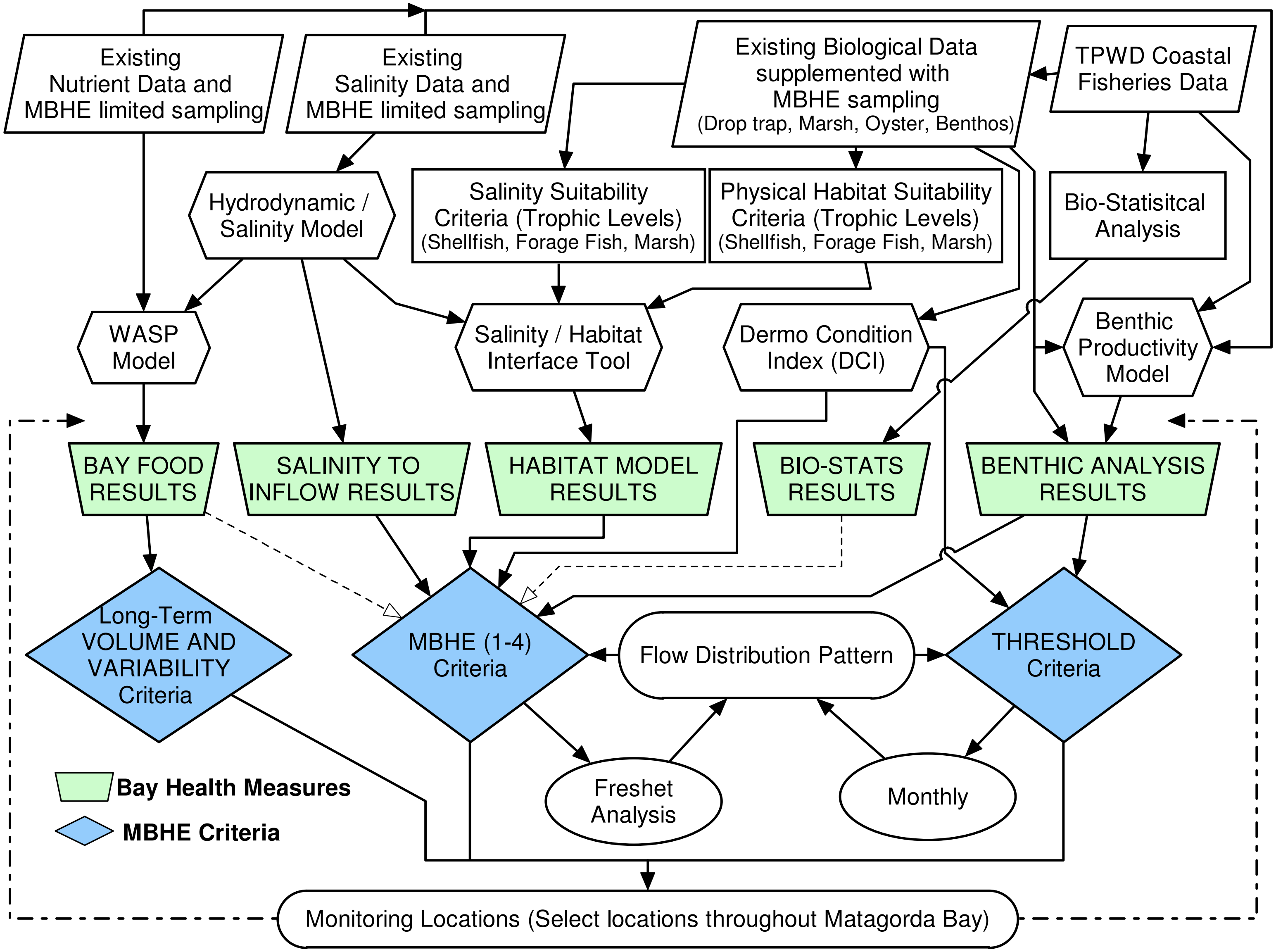


Figure 28. Flowchart summarizing MBHE Freshwater Inflow Criteria Development. Dashed lines represent confirmatory relationships.

The inflow suite for the MBHE inflow criteria includes long-term inflow conditions (presented as long-term volume and variability), an inflow regime (presented as MBHE 1-4), and extremely low and infrequent inflow events (termed Threshold). The MBHE freshwater inflow categories and specific criteria as summarized in Table 10 below include a range of inflows with the goal of providing the essential components to maintain the health and productivity of Matagorda Bay.

Table 10. Inflow Categories and Range of Inflow Criteria.

Inflow Category	Inflow Criteria	Description
LONG-TERM	Long-term Average Volume and Variability	provide adequate bay food supply to maintain the essential food supply and existing primary productivity of the bay system
MBHE INFLOW REGIME	MBHE 4	provide inflow variability and support high levels of primarily productivity, and high quality oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat.
	MBHE 3	provide inflow variability and support quality oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat.
	MBHE 2	provide inflow variability and sustain oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat
	MBHE 1	maintain tolerable oyster reef health, benthic character, and habitat conditions
MINIMUM	Threshold	refuge conditions for all species and habitats

3.1.1 Long-term Average Volume and Variability Criteria

An essential element of the criteria is the need to maintain the flow amounts and patterns that provide a major source of food to support the health and productivity of the estuary and maintain phytoplankton primary production. An important and widely used measure of this primary production is the concentration of phytoplankton chlorophyll-*a* in the water column. Both field data and modeling have confirmed a functional relation between the concentration of chlorophyll-*a* in the EAMB and the amount of inorganic N carried by river inflows. Inflows carrying inorganic N as well as organic matter are important drivers of the ambient level of chlorophyll-*a* and primary productivity in the EAMB, particularly under higher flow conditions, since a large portion of the nitrogen and organic matter loads are conveyed to the EAMB during higher flow events. Maintaining these flow pulses, an important part of the variability, is thus essential to meeting the historical long-term average level of primary productivity.

3.1.2 MBHE Inflow Regime Criteria

The MBHE 1-4 criteria involve an inflow regime aimed at maintaining the health and productivity of Matagorda Bay.

MBHE 4 criteria are recommended to bridge the gap between long-term volume and variability and MBHE 3. MBHE 4 criteria will allow for a high level of primary productivity and when implemented in concert with the other MBHE criteria, enhance the intra-annual variability so valuable to estuarine systems. MBHE 4 criteria would likely take place during average climatic conditions. The reference to climatic conditions just represents conditions that would likely cause salinity ranges associated with these criteria, not operational triggers. The goal for the MBHE 4 criteria is to maintain high quality conditions for oyster health, benthic habitat, low estuarine marsh, and shellfish and forage fish habitat throughout the entire upper EAMB Design Area. This in turn will provide near optimal conditions for all trophic levels within the delta. This spatial expansion of high quality habitat and added inflow variability to the system will assist in maintaining the health and productivity of Matagorda Bay.

MBHE 3 is recommended to support intra-annual variation in the inflow regime. MBHE 3 criteria would likely take place during somewhat below average climatic conditions with the reference to climatic conditions representing conditions that would likely cause salinity ranges associated with these criteria, not operational triggers. The goal for MBHE 3 is to maintain higher quality conditions for oyster health, benthic habitat, low estuarine marsh, and shellfish and forage fish habitat than the lower two MBHE criteria. This spatial expansion of higher quality habitat and added inflow variability to the system will strengthen the MBHE inflow regime.

MBHE 2 is also recommended to provide intra-annual variation and would likely take place during dry but not extreme climate conditions. Again, this just represents conditions that would likely cause salinity ranges associated with this criteria, not operational triggers. The goal for MBHE 2 is to sustain conditions of oyster health, benthic condition, marsh productivity, and shellfish and forage fish habitat. During these relatively dry conditions, the mid-bay region would experience lower quality ecological conditions for each trophic level. Depending on inflows from the Lavaca Basin, it is also likely that during these conditions the reefs, benthic habitat, low estuarine marsh, and shellfish and forage fish habitat would be largely reduced further west into the Matagorda Bay system. These low inflow and higher salinity conditions have been experienced in the past and will no doubt be experienced in the future, and, as previously noted, play an important ecological role in an estuary.

MBHE 1 embodies salinity conditions that would naturally be experienced during fairly extended dry conditions, though less extreme than those experienced at the Minimum inflow category. These climatic conditions are descriptive of what it would likely take to cause the salinity ranges associated with this criteria, but do not imply operational triggers. Although the role of low flows may not always appear as beneficial based on modeling results, they do support the long-term variability to which native species have evolved. Important roles include marsh die-off, promoting native species, and promoting genetic strengthening. Marsh die-off provides organic matter input not only for nourishment of the soils for continued marsh development but also as a source of bay food (Teal 1962, Wilson et al. 1986, Delaune et al. 1983). Higher salinities and other water quality parameters are extreme conditions that are observed naturally. Experiencing these natural extremes puts stress on non-native species and promotes the survival of the fittest concept within the native flora and faunal community (Poff and Allan 1997, Bunn and Arthington 2002). The variability (frequency, duration, and timing) along with the delivery (freshet vs. calendar month) of inflow during these periods has been proven to be significant. As discussed for Threshold criteria below, extended low-flow periods also have negative effects that may alter the character of the bay if experienced outside the realm of historical conditions.

3.1.3 Threshold Criteria

Extremely low freshwater inflow conditions (i.e., at or near drought of record) do occur in natural systems. An estuary is different than a river in that a bay will not go dry with no inflow. This condition allows some level of habitat to remain, but it worsens as the bay gets saltier, warmer, has less food supply, etc. Short periods of such extreme conditions can provide benefits that include marsh die-off (source of organic matter input to the bay) and genetic strengthening (survival of the fittest). However, continued conditions can lead to excessive marsh die-off which can destabilize marsh sediments leading to erosion and overall marsh loss. Positives and negatives relative to an estuarine inflow regime are the foundation for ecological variability and the long-term health of an estuary. It is the frequency and duration of these extremely low flow to no inflow periods that, if extended beyond the natural tendency of the bay, can shift the ecological community to a more saline tolerant assemblage (e.g., Laguna Madre). While the Laguna Madre is considered a healthy and productive system, its condition would likely not meet the test of "maintaining the health and productivity of Matagorda Bay."

3.2 Design Areas

Application of the habitat, oyster, benthic, and nutrient models, along with the hydrodynamic/salinity model, to establish freshwater inflow criteria requires the use of design areas within the system. These design areas constitute the area of the bay system in which the response to various Colorado River inflow volumes will be measured using the MBHE modeling and analysis tools. The overall focus is placed on the EAMB since that is the area most likely to be directly impacted by the LSWP. Three design areas were chosen and correspond with level of inflow. The design areas for each inflow criteria are listed below and depicted in Figure29. Note that as the freshwater inflow specific to the Colorado River decreases, the spatial (longitudinal) extent of the design area also constricts.

Inflow Criteria	Design Area
Long-term Average Volume and Variability	Eastern Arm of Matagorda Bay
MBHE 1, 2, 3, 4	Delta Edge to Mad Island Reef Transect
Threshold	Colorado River Delta

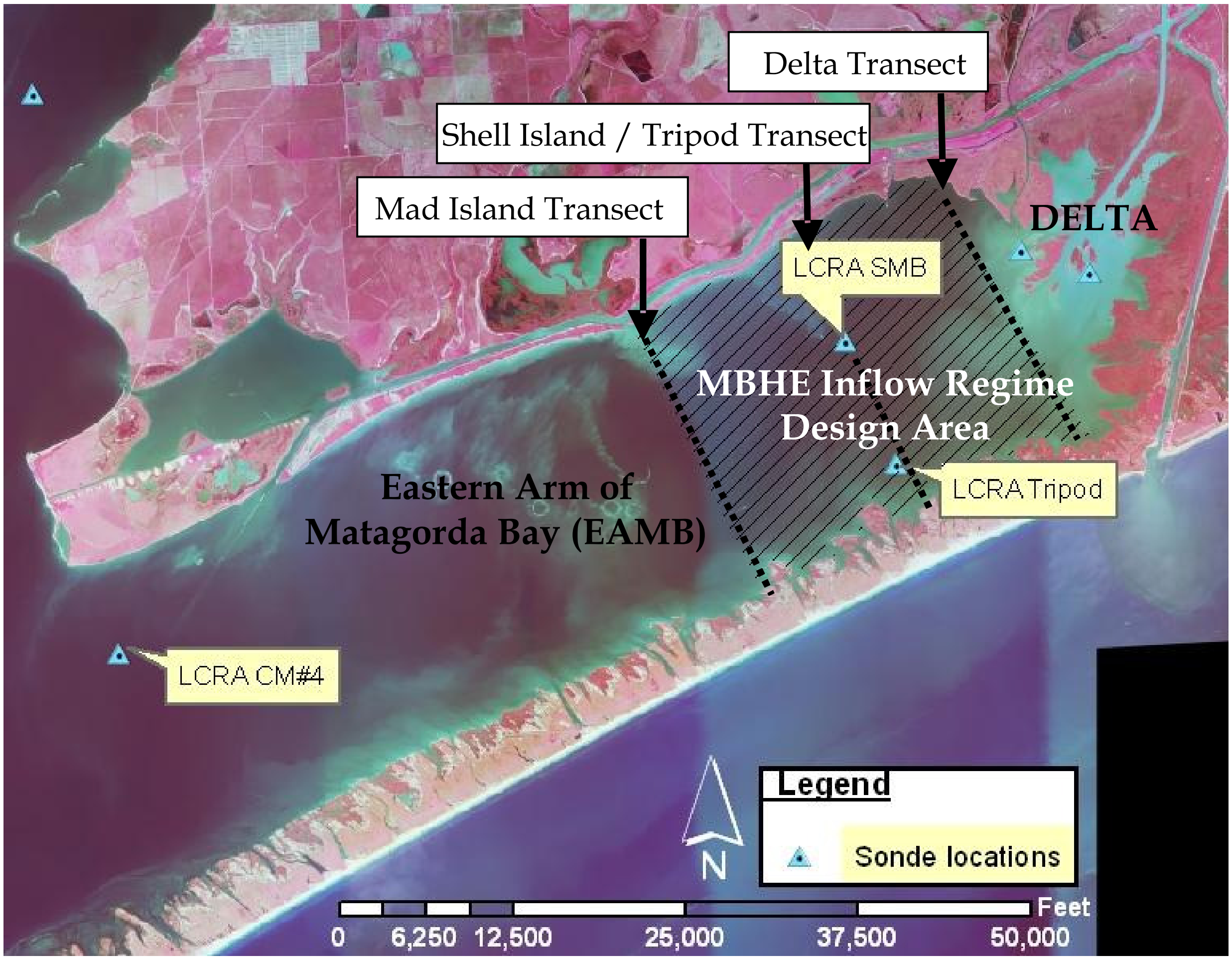


Figure 29. Map of proposed upper EAMB Design Area extending from the edge of the Colorado River Delta to a north/south transect through the Mad Island Oyster Reef.

The entirety of the EAMB serves as the design area for the long-term volume and variability criteria. High inflow events (via the Colorado River) which are one component of the long-term volume and variability criteria have the ability to provide freshwater throughout the entire EAMB, and beyond under very high inflow conditions. Response of chlorophyll-*a* throughout the EAMB provides the primary basis for establishment of the long-term volume and variability criteria levels.

The MBHE Inflow Regime criteria design area was selected based on the variability of habitat types, key species present, and the ability to relate freshwater inflow from the Colorado River to salinity changes within the design area with a reasonable level of confidence. The ability to predict the salinity to inflow relationship for the design area is paramount to the success of the MBHE inflow criteria. The MBHE Inflow Regime design area extends from a transect at the edge of the Colorado River delta to a north/south transect stretching from the Mad Island oyster reef on the north to the barrier island on the south (See Figure 29). This design area includes approximately 13,000 acres within the east/central portion of EAMB which when coupled with approximately 7,500 acres in the delta equates to over 45% of the entire EAMB. The key habitat features discussed in section 2.2 (estuarine marsh, oyster reefs, submerged aquatic vegetation, and shallow non-vegetated bottom) along with all key species being evaluated are found within this design area. Specific features also influencing the selection of this design area include the Shell Island oyster reef, Mad Island oyster reef, LCRA West Bay Tripod, LCRA Shell Marker B data sonde, and long-term benthic monitoring station F (see Figure 16, section 2.4.1). Mad Island and Shell Island oyster reefs are commercially harvested with moderate to low levels of dermo infection and both are routinely sampled under the DermoWatch program. Including the entire area encompassed within the MBHE Inflow Regime Design Area also captures any north to south salinity gradient influenced by Colorado River inflow, localized watershed runoff events, wind and tides. Most importantly, this Design Area is close enough to the Colorado River input to allow confidence in the salinity to inflow relationships discussed in Section 4.0.

The Colorado River Delta region is utilized as the Threshold Design Area. The Delta is the area most directly influenced by Colorado River flows and thus provides the best opportunity for potentially maintaining refuge conditions during these extreme periods. The Colorado River Delta is currently an actively forming delta that supports a vibrant low estuarine marsh community and approximately 20% of the oyster reef area present in the EAMB (MBHE 2007a). The MBHE field work conducted during 2006, 2007, and 2008 document the importance of this region as a nursery to shellfish (brown shrimp, white shrimp, and blue crab) and forage fish (Atlantic croaker and Gulf menhaden). The limited dermo sampling conducted in Spring 2007 and Summer 2008 document that dermo does exist on the expanding oyster reefs within the Delta, but at concentrations below levels of concern. The oyster reefs located in the Delta are not commercially harvested and are shallow water tidal reefs as opposed to the deeper more established reefs further west in the EAMB (e.g., Shell Island Reef, Mad Island Reef).

It is important to distinguish between the Design Areas described above and monitoring locations which might be established to assess the sufficiency of the recommended Inflow Criteria. The Design Areas are not meant to be synonymous with long-term monitoring areas or somehow exclusively linked to future assessment of inflow criteria. No doubt, long-term monitoring activities will take place within the Design Areas, but are not limited to these areas. Recommended long-term monitoring will include select locations throughout the Matagorda Bay system. For example, existing benthic monitoring stations are located within the entire Matagorda Bay system (see Figure 16, section 2.4.1). Sammy's reef will also be a key monitoring location during all inflow conditions even though it does not geographically fall within the MBHE Inflow Regime or Threshold Design Areas.

A continual assessment of the effectiveness of inflow criteria is a vital part of the recommended monitoring program. Assessment is not based on pass/fail criteria at a given point in time, rather an evaluation of chemical, physical, and biological data collected over time or produced via model output where applicable. This assessment will put to use data collected via the MBHE long-term monitoring program, existing monitoring programs within the system, and for reference conditions sometimes beyond the system, and the full suite of MBHE tools. Data from within the Design Areas will be used to assist this assessment, but not in an exclusive manner.

3.3 MBHE Inflow Criteria

As depicted in Figure 28, multiple tools were developed and selectively applied to generate inflow criteria for the lower Colorado River contribution to Matagorda Bay. Once the Design Areas were determined, specific calculations of long-term bay food inputs, oyster reef health, benthic character, and habitat conditions were made for various components of each criteria as described in Section 2.0. The following subsections describe how each freshwater inflow criteria was selected and its basis. In the case of Long-term Volume and Variability (Section 3.3.1), the use of the nutrient modeling allows direct development of the recommended inflow criteria. However, for the remainder of the inflow criteria suite, it will be necessary to further employ the salinity/inflow relationships and apply a seasonal distribution in order to complete the development of the flow recommendations. These remaining factors will be discussed in Sections 4.0 and 5.0.

3.3.1 Long-term Volume and Variability

As discussed in Section 3.2, the Design Area for the long-term volume and variability category is the EAMB. The objective of this criteria is to maintain historical levels of bay productivity and primary productivity, as represented by chlorophyll-*a*. This presumes that there is a direct relationship between inorganic-N and organic matter carried by inflows and bay chlorophyll-*a*, and that there is a critical tie between flow variability and system productivity. Both of these presumptions are supported by the nutrient data analysis and modeling described in Section 2.6 and fully documented in MBHE 2007c.

The EAMB flow values (ac-ft/year) computed with the WASP model to meet the post-diversion median and average chlorophyll-*a* values and the expected range are:

	To meet median	To meet average
Flow needed for model to meet Post- diversion chlorophyll-*a*	1,288,000	1,546,000
Flow needed for model to meet lower limit of expected range of Post- diversion chlorophyll-*a*	1,011,000	1,273,000
Flow needed for model to meet upper limit of expected range of Post- diversion chlorophyll-*a*	1,559,000	1,820,000

For comparison, the actual inflows to the EAMB were:

	Median	Average
EAMB Flows,1977-2005 (period of chlorophyll-*a* record)	552,000	1,251,000
EAMB Flows.1995-2002 (calibration period)	837,000	1,939,000
EAMB Flows,1993-2005 (post-diversion)	911,000	1,969,000

The selected inflow needs to be protective of the level of EAMB primary productivity. Given that different quantification approaches will yield slightly different answers to the same question, an inflow volume of 1,300,000 ac-ft/year to the EAMB, or approximately 1,400,000 to 1,500,000 ac-ft/year in the lower Colorado River, is the flow volume recommended to maintain the average chlorophyll-*a*. This average flow value is somewhat lower than the amount needed to meet the average post-diversion chlorophyll-*a* (1,546,000), but is higher than the amount needed taking into account the expected range on the data (1,273,000). As shown in Figure 30, the 1,300,000 ac-ft/year value is not substantially different from the post-diversion condition and considerably higher than the pre-diversion flows to the EAMB. To assure that this long-term average flow is effective in that it continues to include the required high flow periods, it should be accompanied by a monthly CV of

0.8, a lower bound typical for the post-diversion period and a value rarely exceeded in the pre-diversion years.

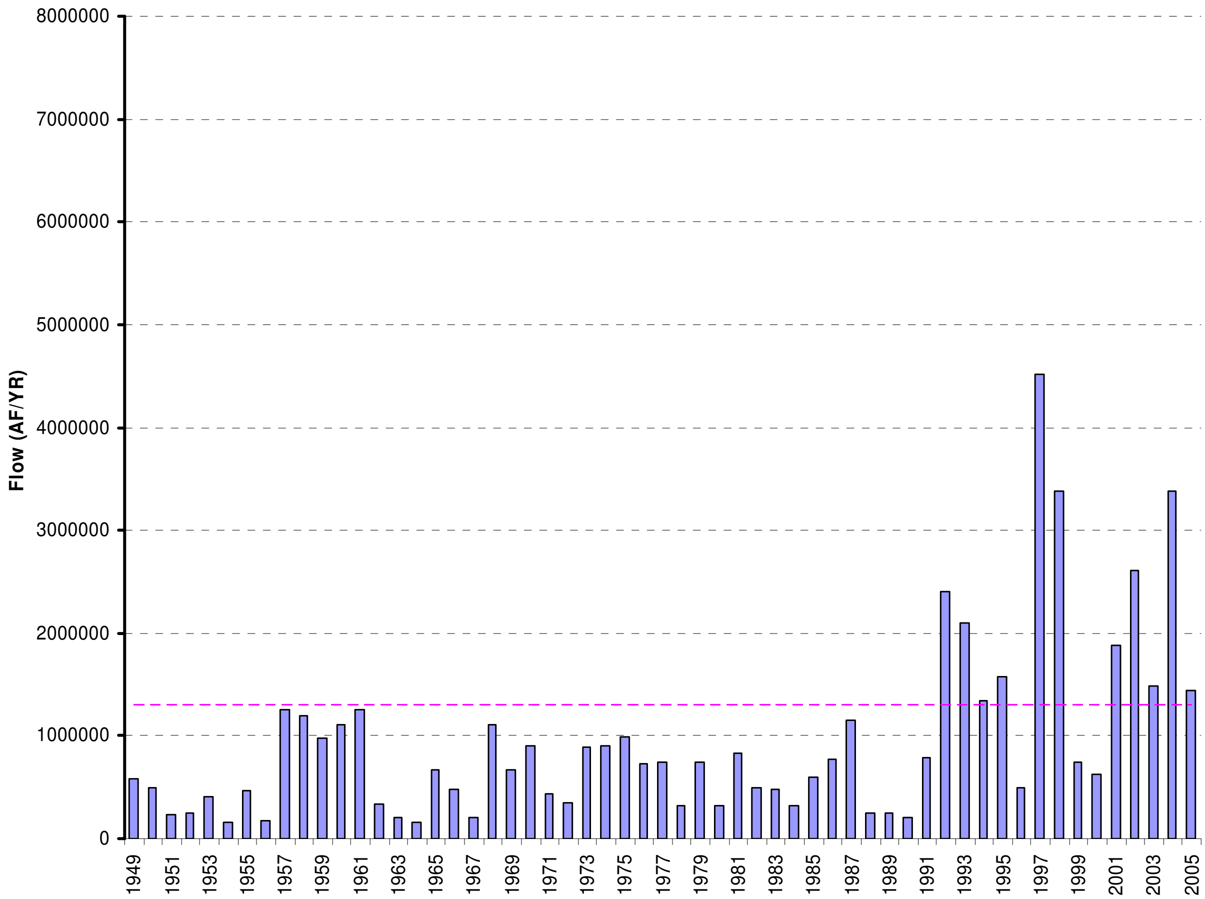


Figure 30. Historical flow into the EAMB. Colored dashed line is 1,300,000 ac-ft/yr – the long-term average inflow criteria.

3.3.2 MBHE Inflow Regime

Once the MBHE Inflow Regime Design Area (see- Figure 29) was determined, salinity ranges were established over the existing physical habitat that would provide ecological conditions suitable to maintain the health and productivity of Matagorda Bay. These ranges were based primarily on the habitat model results (Section 2.2) and benthic analysis (Section 2.4). The goal for this assessment was to provide extremely good or high quality conditions at the higher end of the inflow spectrum while maintaining conditions not uncommon (albeit limited) to the Matagorda Bay system during extremely low flow conditions. There were two parts to this assessment; the first involved describing the habitat conditions that are present in the Design Area within a range of inflows within this spectrum, using salinity as a surrogate for inflow. The second phase was to establish achievement guidelines to incorporate the frequency, timing, and duration of such conditions within the broader context of Matagorda Bay hydrology and ecology (discussed in Section 5.0).

For the habitat assessment, the highest inflow category within the Inflow Regime spectrum (MBHE 4) was chosen to support good or better habitat conditions within the Design Area for all species evaluated. This equates to at least 75% of the maximum amount of available habitat for each species being provided at all times within the Design Area. Additionally, a simultaneous goal for this criteria was to provide selected conditions for all modeled species within the Colorado River Delta. Selected relates to 90 to 100% of the maximum amount of available habitat for a given species and the Colorado River Delta is defined as the area inside the Delta Edge transect (see Figure 29). The goal for the remaining MBHE inflow criteria in this spectrum was to stair step down in quality of habitat but maintain similar conditions to what was observed historically in the Design Area and within the Delta. As previously discussed, four MBHE inflow regime criteria were selected to promote intra-annual variability. The four inflow criteria, as established in the MBHE inflow spectrum based on habitat modeling activities, are shown below.

Inflow Category	**Modeled Species Rank within MBHE Design Area**	**Modeled Species Rank within Delta region**
MBHE 4	All species good or selected	All species selected
MBHE 3	All species fair or better	All species good or selected
MBHE 2	All species poor or better	All species fair/poor or better
MBHE 1	About half poor and half refuge	All species poor (except Atlantic croaker [refuge])

The DCI model results are included for the MBHE inflow regime criteria, but as discussed in Section 2.3.3 must be viewed with caution as it is not possible to directly relate the DCI results to a set salinity range as presented in Table 12. As discussed in Section 2.3.3, the DCI model uses time dependent variables, dermo infection is a multi-year phenomenon and the percentage of infection also plays a role in the level of dermo weighted incidence. Figure 31 shows the 2YS to dermo weighted incidence relationship for the four temperature regimes evaluated in Section 2.3.4 with the MBHE inflow regime criteria salinity ranges overlaid on the figure for discussion in the following sections.

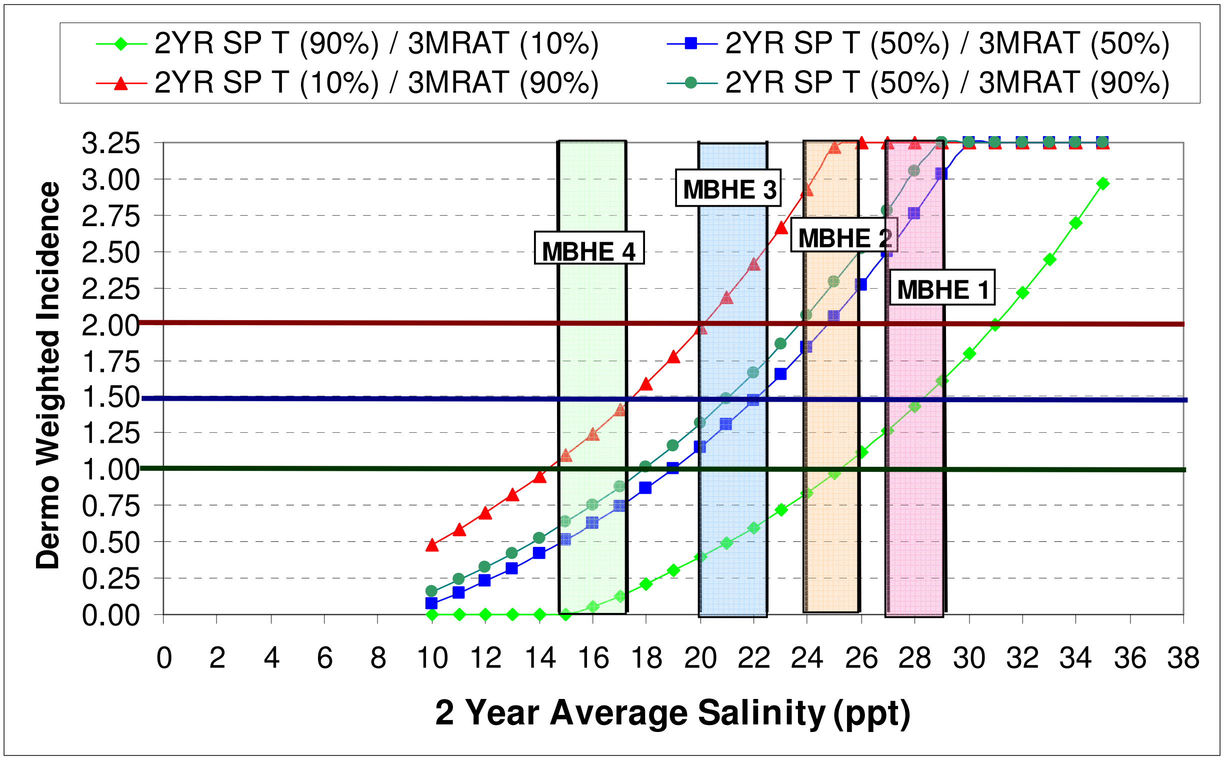


Figure 31. Two-year rolling salinity versus dermo weighted incidence relationship for four temperature regimes representing average and more extreme conditions. MBHE 1, 2, 3 and 4 salinity ranges are overlain on the chart to aid in interpretation in the following sections.

MBHE 4

The objectives of MBHE 4 inflows are to provide a condition that constitutes good to optimal conditions for the various trophic levels evaluated and creates intra-annual variability in the flow regime when coupled with the other MBHE inflow regime criteria. A salinity range of 15-18 ppt over the Design Area was selected to meet these objectives for MBHE 4. This salinity range suggests higher inflows that would in turn support a high level of primary production within the EAMB (Section 2.6). At this salinity range, greater than 75% of the maximum habitat over the entire Design Area is provided for all trophic levels that were evaluated with the habitat model. This results in good to selected conditions for the trophic levels (Figures 9-13, Section 2.2.1). The benthic analysis documents that the mean salinity at Station F (near the West Bay Tripod) during post-diversion benthic monitoring was 18.6 (Table 5, Section 2.4.4), which is higher than the MBHE 4 salinity range. An examination of Figure 31 shows that dermo weighted incidence values would be less than 1.0 with constant salinities over the two-year period and constant temperatures represented as average for both terms and average spring temperatures coupled with nearly extreme summer temperatures. The extremes as described in Section 2.3.3 and presented in Figure 31 predict very good (almost no dermo) conditions during positive extremes (bright green line with diamonds) and moderate (between approximately 1.5 and 1.0) conditions during negative extremes (red line with triangles), relative to dermo weighted incidence. Based on the categories described in Section 2.3, overall MBHE 4 is interpreted as maintaining good oyster health conditions. With respect to key species, using Atlantic croaker and white shrimp as indicators for any species dependent on the spring or fall freshet, respectively, the regressions of abundance versus freshet flow indicate that if all of the other sources of the variance in abundance except inflow remain the same, then when the MBHE 4 flow magnitude is achieved (i.e., equaled or exceeded), the probability that the median historical abundance will be achieved is about 90% and that the minimum historical abundance will be achieved is nearly 99%.

MBHE 3

The objectives of MBHE 3 inflows are to provide a condition that constitutes fair to good conditions for the various trophic levels evaluated and supports intra-annual variability. A salinity range of 20-23 ppt over the Design Area was selected to meet these objectives for MBHE 3. This salinity range will require higher inflows than the other MBHE inflow regime criteria thus representing the highest amount of primary production during these conditions. At this salinity range, greater than 50% of the maximum habitat available across the Design Area is provided for all trophic levels that were evaluated with the habitat model. This results in fair to good conditions for the trophic levels presented under MBHE 3 (Figures 9-13, Section 2.2.1). The benthic analysis suggests conditions are less favorable than at MBHE 4 because as salinity conditions start to change greater than about 20% from the long-term average (this starts to happen at the upper end of the MBHE 3 salinity range), a change in benthic community structure, biomass, and diversity for both deposit feeders and suspension feeders in Matagorda Bay (Figure 21, Section 2.4.4) starts to occur. MBHE 3 salinities exceed the post-diversion mean salinity (18.6) at Station F, but still fall below the mean salinity at Station E (near the edge of the EAMB) (Table 5, Section 2.4.4). An examination of Figure 31 shows that dermo weighted incidence values would be between approximately 1.0 and 1.5 with constant salinities over the two year period and constant temperatures represented as average for both terms, and average spring temperatures coupled with nearly extreme summer temperatures. The extremes as described in Section 2.3.3 and presented in Figure 31 show good conditions (less than 1.0) during positive extremes (bright green line with diamonds) and very poor conditions (exceeding 2.0) during negative extremes (red line with triangles), relative to dermo weighted incidence. Based on the categories described in Section 2.3, overall MBHE 3 is interpreted as maintaining fair oyster health conditions.

MBHE 2

MBHE 2 inflows are recommended to provide a mid-level MBHE flow to assist inflow variability and to maintain ecological conditions similar to those historically observed at these inflow levels. A salinity range of 24-26 ppt over the MBHE Design Area was selected to meet these objectives for MBHE 2. This salinity range provides for inflows that would provide primary production levels between the other MBHE inflow categories. At this salinity range, greater than 25% of the maximum habitat available across the Design Area is provided for all trophic levels. The benthic analysis suggests conditions are less favorable than at MBHE 3 because all salinities within this range are greater than 20% from the long-term average at Station F likely resulting in a change in benthic community structure, biomass, and diversity for both deposit feeders and suspension feeders in Matagorda Bay (Section 2.4.4). MBHE 2 salinities now encompass the post-diversion mean salinity for Station E, but are still within the mean salinity plus 1 standard deviation at Station F (Table 5, Section 2.4.4). As discussed above, the post-diversion hydrology is a considerably wetter hydroperiod when compared to the period of record. An examination of Figure 31 shows that dermo weighted incidence values are predicted between approximately 1.75 and 2.25 with constant salinities over the two-year period and constant temperatures represented as average for both terms, and average spring temperatures coupled with nearly extreme summer temperatures. The extremes as described in the previous section and presented in Figure 31 still show good (~1.0) conditions during positive extremes and potential detrimental (approaching the highest post-diversion dermo levels recorded) conditions during negative extremes, relative to dermo weighted incidence. Based on the categories described in Section 2.3, overall MBHE 2 is interpreted as maintaining poor oyster health conditions with the potential for infrequent detrimental effects.

MBHE 1

The objectives of MBHE 1 inflows are to maintain ecological conditions similar to those historically observed at these inflow levels while providing another level of inflow variability. The goal is to maintain tolerable oyster reef health, benthic character, and habitat conditions to the degree practical during these conditions. A salinity range of 27-29 ppt over the Design Area was selected to meet these objectives for MBHE 1. This salinity range provides the lowest MBHE inflows thus also the lowest primary production within the system compared to the other MBHE inflow categories. At this salinity range, all trophic levels that were evaluated with the habitat model are represented by poor to refuge conditions. This salinity range is outside of the mean salinity plus 1 standard deviation for post-diversion benthic monitoring at Station F (Table 5, Section 2.4.4). Compared to MBHE 2, greater changes in benthic community structure, biomass, and diversity for both deposit feeders and suspension feeders would be prevalent in the MBHE 1 range (Section 2.4.4). A shift from euhaline to marine benthic assemblages has the potential to occur at the upper end of this range, with a complete shift likely to occur above this range. The DCI model shows that with constant salinities in this range over the two-year period and constant temperatures represented as average for both terms, and average spring temperatures coupled with nearly extreme summer temperatures, dermo weighted incidence could be detrimental. Under the positive extreme, refuge areas for oysters would still be available, but under the negative extreme, dermo conditions would be expected to match or exceed some of the highest dermo levels recorded in EAMB. A key aspect to all MBHE inflow regime criteria is the application of achievement guidelines to be discussed in Section 5.0.

3.3.3 Threshold

As discussed above, during Threshold conditions, the majority of the EAMB is experiencing high salinity conditions with limited nutrient input. Throughout the historical record, the reduction of inflow levels has never eliminated any of the key species addressed in this bio-statistical effort (shown by the absence of any zero values of annual-mean abundance in the data record). Also, these populations continue to exist at more-or-less historical levels, so reduction of inflow levels does not preclude the re-establishment of the population after a population reduction. Therefore, the data record does not reveal a level of inflow that is, in some sense, catastrophic for any one of these species, and which, therefore, would have to be exceeded at all times. However, future conditions will likely change, and to be conservative, the threshold recommendation is included as a criteria which would attempt to avoid experiencing a catastrophic event.

The ecological objectives during these extreme periods are to sustain live oysters, maintain estuarine benthic character, and provide refuge habitat for shellfish and forage fish to the extent possible. Thus, the Design Area of the immediate Colorado River Delta was chosen because of the direct relationship of Colorado River inflow to the Delta during these extreme drought conditions. An evaluation of the percentage of time that this condition was historically experienced or exceeded, along with the 27 ppt salinity bound (Station F mean salinity plus 1 standard deviation) from the benthic analysis were used to set the Threshold criteria. To accomplish these objectives to the degree practicable during extreme droughts, a minimum inflow is recommended to maintain salinity conditions in the Delta below 30 ppt. One goal of maintaining this level of inflow is to provide refuge areas for shellfish and forage fish outside of the main river channel. Maintaining this level should protect the estuarine benthic character in at least portions of the Delta. Based on the DCI model, even salinities near or above 30 ppt might not be detrimental to oyster health via dermo infection for some period of time, when considering the memory component of oyster health. Conversely, the level of dermo infection during extreme temperatures often accompanying these periods of extended low inflow may cause extensive mortality. Similar to nature, there are no guarantees, and thus oyster and dermo monitoring during these periods will be vital to guide potential adaptive management opportunities aimed at protecting live oysters within the Delta during these extreme events.

3.3.4 Summary

As described above, multiple tools were developed and applied to generate the three inflow categories (long-term, regime, and minimum) and resulting six inflow criteria:

Long-Term

- *Long-term volume and variability*

MBHE Inflow Regime

- *MBHE 4*
- *MBHE 3*
- *MBHE 2*
- *MBHE 1*

Minimum

- *Threshold*

Table 11 summarizes the freshwater inflow criteria, Design Areas the tools were applied at, salinity ranges predicted at those Design Areas, and associated trophic level condition descriptors. For the Long-term volume and variability criteria, higher and lower flows are encompassed, therefore it is not possible to directly fill in the last column in Table 11. A wide range of salinity would be expected over time as would variable conditions (refuge, poor, fair, good, selected) for all trophic levels.

Table 11. Summary of Freshwater Inflow Criteria, Design Areas, salinity ranges, and associated trophic level condition descriptors.

	Threshold	MBHE 1	MBHE 2	MBHE 3	MBHE 4	Long-term Volume and Variability
Design Area	Delta	Delta Edge to Mad Island Transect	Delta Edge to Mad Island Transect	Delta Edge to Mad Island Transect	Delta Edge to Mad Island Transect	EAMB
Salinity range across area (ppt)	< 30[1]	27-29	24-26	20-23	15-18	Average[4]
Trophic Level						
Primary Production	Low	Low	Low	Moderate	High	Normal[5]
Oyster Health	Refuge[2]	Refuge[2]	Poor[2]	Fair	Good	Normal[5]
Benthic Condition	Fair / Poor	Poor	Fair	Good	Peak	Normal[5]
Marsh Productivity	Fair	Fair	Good	Good	Good	Normal[5]
Shellfish Habitat	Good[3] / Poor	Good[3] / Poor	Selected[3] / Fair / Poor	Selected[3] / Fair	Selected[3] / Good	Normal[5]
Forage Fish Habitat	Poor / Refuge	Poor / Refuge	Poor	Fair	Good	Normal[5]

[1] This would be typical when no significant local watershed inflows have occurred.

[2] Potentially detrimental to select reefs based on Dermo Condition Index. However, a condition experienced a similar amount of time historically.

[3] Ranking applies to brown shrimp. Blue crab and white shrimp habitat ranks lower.

[4]The long-term average salinity will be in the mid teens but include very low and high periods.

[5]Indicators of productivity and health will be normal, but will experience variations during dry and wet periods.

4.0 Salinity to Inflow Relationship for the Upper EAMB Design Area

Thus far, the habitat conditions related to a spectrum of inflow are still expressed as ranges of salinity. This is the case for all criteria categories with the exception of long-term. In order to complete the primary purpose of developing numerical Inflow Criteria for the Colorado River for all criteria categories, it is necessary to translate these desired salinity conditions in the Design Areas into Colorado River flow volumes that can be expected to produce the desired salinities. The primary tool for constructing this relationship is the MBHE hydrodynamic/salinity model described in Section 2.1. The model has the ability to depict salinity at any desired location in the bay and with full flexibility to assign model inputs. The model has been run over an 8.5-year period, and the resulting model computations have been compared with sonde measurements from throughout Matagorda Bay (see MBHE 2006b and MBHE 2008).

Salinities — and therefore habitat condition —in the design areas are controlled primarily by inflow from the Colorado River. There are, however, other influences on these salinities, including open bay salinities and the inflow from the coastal watershed adjacent to the EAMB. For now, we regard these additional factors as contributors to variance of salinity, i.e. “noise.”

The primary flow time-series to be evaluated for its relationship to salinity in the EAMB, based on operation of the hydrodynamic/salinity model, is the inflow conditions consisting of Colorado River at Bay City flows minus the South Texas Project (STP) diversions.

The period July 1995 through December 2003 has been simulated in the hydrodynamic and salinity model (see MBHE 2006b). This period was selected so as to encompass a wide range of flow conditions, both high and low, all during the post-Diversion period within a short-enough calendar period that model simulation was feasible. As depicted in Figure 32, the period includes two sustained low flow periods; namely, the 20-month period from July 1995 through February 1997, and the 22-month period from January 1999 through October 2000. It also encompasses a 22-month high flow period from March 1997 through December 1998.

For the entire 8.5 year model period, salinity time-series were extracted from the salinity model output at model nodes corresponding to the three transects across the Design Area. The model output at each node was averaged daily, and then these resulting daily salinities were averaged along each of the three transects (Mad Island Reef, Shell Island/Tripod, and edge of Delta) in order to filter out the intradiurnal variation due to tides. The resulting representation of salinity for the Design Area is three time series of daily average transect salinities over the full 8.5-year simulation period. These salinity time series are shown in Figure 33.

As noted earlier, the input to the hydrodynamic model of primary importance is the flow from the Colorado River into the Matagorda Bay system. This input was developed using the gage records of stream flow at the USGS gage at Bay City, adjusted by withdrawals by STP, which occur downstream from the gage. Except under conditions of very high flow, the salinity in the bay does not react instantaneously to changes in river flow; rather, there is a certain amount of “memory” or “inertia” in the bay, and salinity conditions are driven by the flows experienced over some past time period. After testing several lag periods, it was determined that, on a long-term basis, flow was adequately characterized by the antecedent 30-day volume. Hence, the daily flow time series to

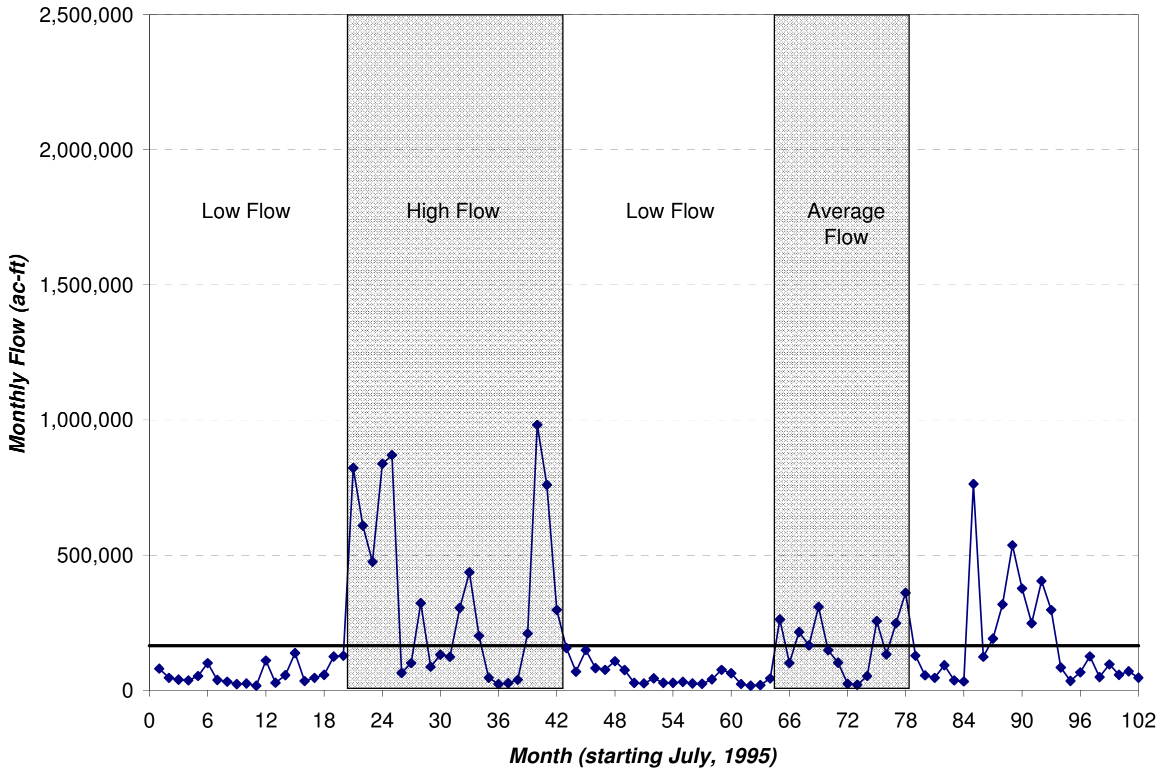


Figure 32. Colorado River at Bay City flow (less STP diversions) over 8.5-year simulation period.

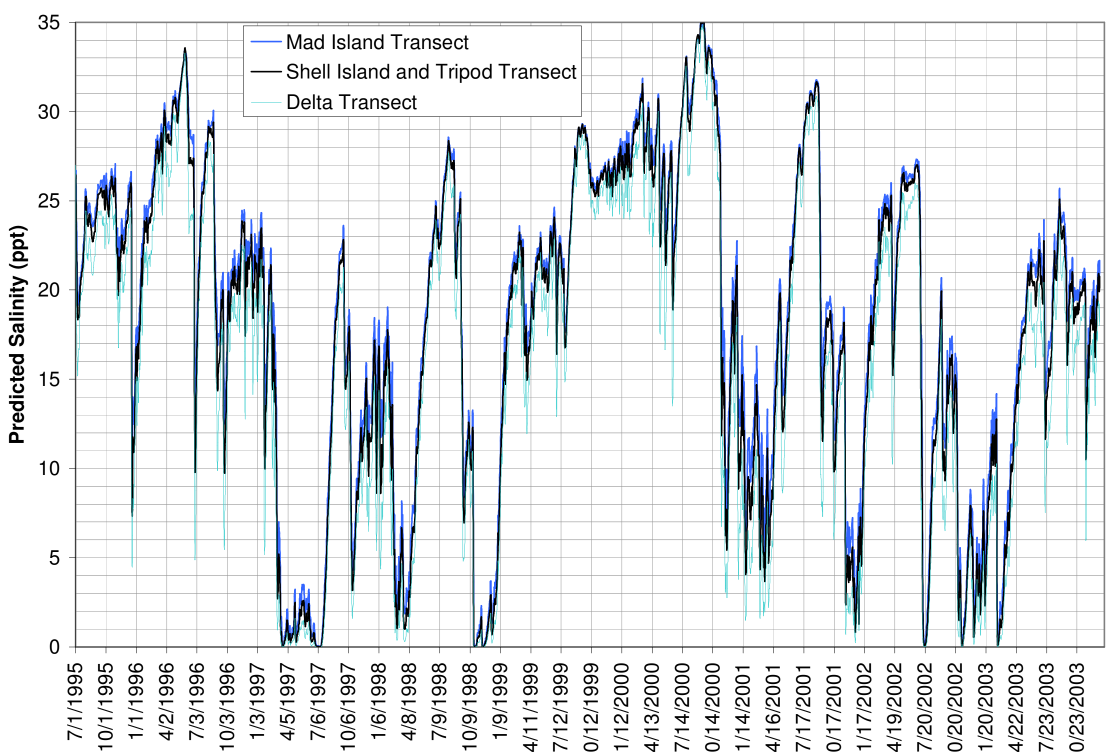


Figure 33. Predicted salinity at design-area transects for 8.5-year simulation period.

compare with the daily transect salinity values was chosen to be the sum of river flows for that day plus the previous 29 calendar days.

The choice to characterize flow as cumulative antecedent 30-day volume represents a compromise. No doubt, the model period includes instances where salinity response to flow volume was:

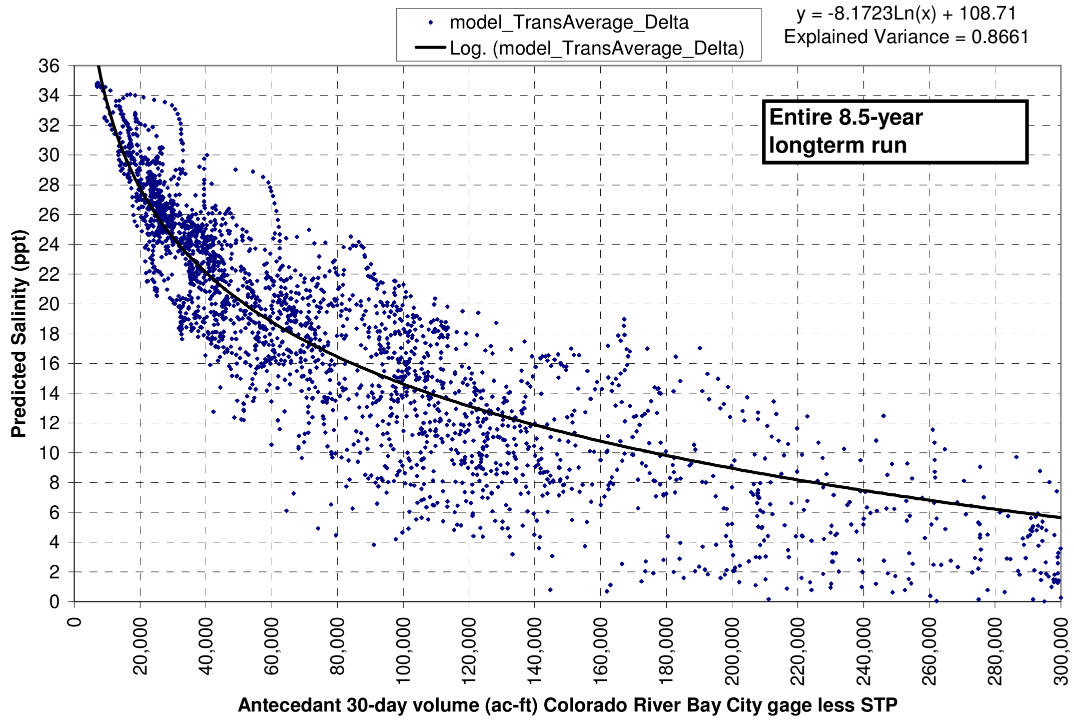
- shorter than 30 days (e.g., a small flow pulse concluded 25 days prior and the salinity had fully recovered 15 days prior);
- longer than 30 days (e.g., a large inflow event occurring more than 30 days prior reduced salinities to near 0 ppt, which may take longer to return to more normal levels); and
- affected by disproportionate inflow contributed by watersheds other than the Colorado River and EAMB coastal watersheds (e.g., Lavaca watershed and other coastal watersheds).

While these points add variability to the set of salinity-volume pairs, there is no practical method to exclude them from the collection and in fact they are indicative of the complex relationship between salinity and flow. The current salinity was related to the antecedent 30-day volume as a means of acknowledging the "memory" of salinity in response to inflow volume (particularly to large antecedent volumes) while realizing that short-term response of salinity to small pulses of flow may be smoothed somewhat.

The collection of daily average salinity-antecedant 30-day flow pairs from the entire 8.5 year model period are displayed on Figures 34 through 36 for the Mad Island Reef, Shell Island/Tripod, and edge of Delta transects, respectively. In addition to the full model period, a reduced "dry period" or low-flow data set is also included in each of these figures. The reduced set includes salinity-flow pairs from the combined 20 and 22 month low flow periods described above; pairs occurring in the first month of each low flow period are omitted to remove influence on 30-day flow of the high-flow days occurring prior to the low flow period.

As a final step to use the long-term hydrodynamic/salinity model results to establish a straightforward relationship between Colorado River inflow and salinity in the Design Area, the daily data has been fit with a regression equation on log-transformed volume, from which flow values corresponding to specified salinities can be determined. The resulting regression equations are also shown on each of the Figures 34 through 36 for each transect. Note that the regression equations have been derived for both the full model period and the combined 20- plus 22-month low flow period.

In order to apply the regression equations as a simple predictor of salinity vs flow at any of the three Design Area transects, we must decide when to utilize the full 8.5 year regression relationship, and when to employ the low flow equation. Figure 37 shows the two regression relationships for the Shell Island/Tripod transect, and Table 12 is a tabular summary of the flows that relate to certain salinity values based on the two equations. Since the 30-day flow volumes during the low flow periods were predominantly below 60,000 ac-ft, it was determined that the normal equation should apply at approximately that value and above, and the "dry-period" equation below about 30,000 ac-ft. So as to effect a smooth transition, a linear interpolation between the two regression equations was employed from 21 ppt to 27 ppt (which correspond approximately to the 30,000 – 60,000 ac-ft range). This process was repeated for the other transects, again using salinity transition points corresponding to the 30,000 – 60,000 ac-ft range, resulting in a single predictive equation to relate inflow to salinity at each transect as shown in Figure 38.



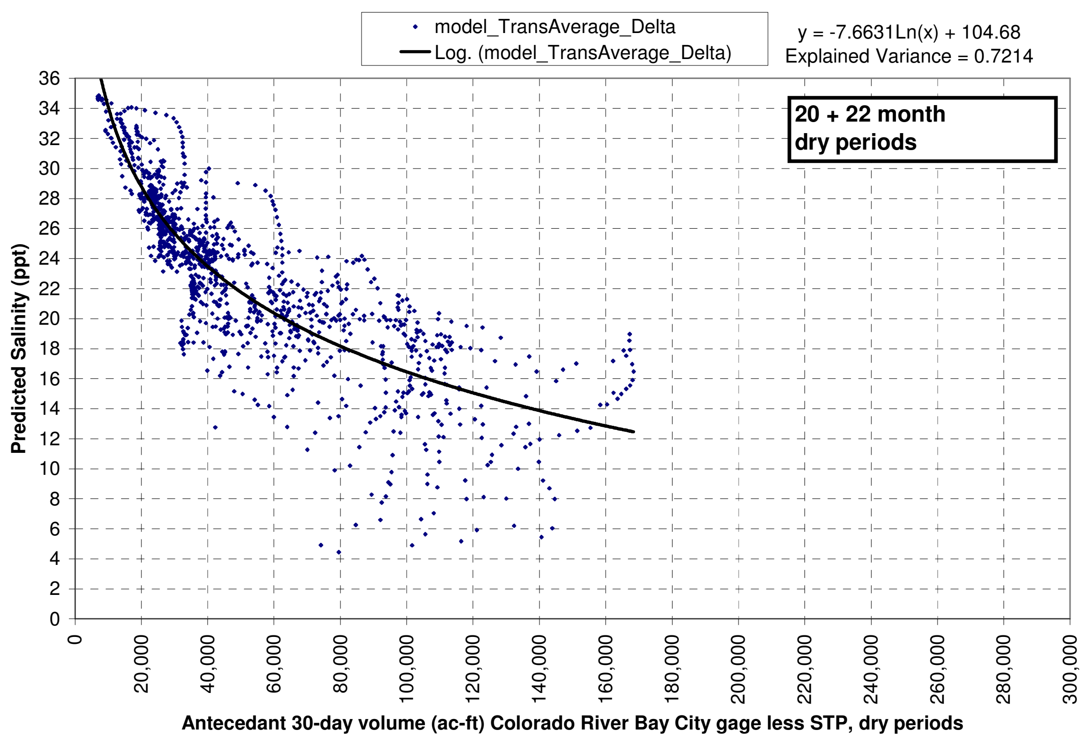
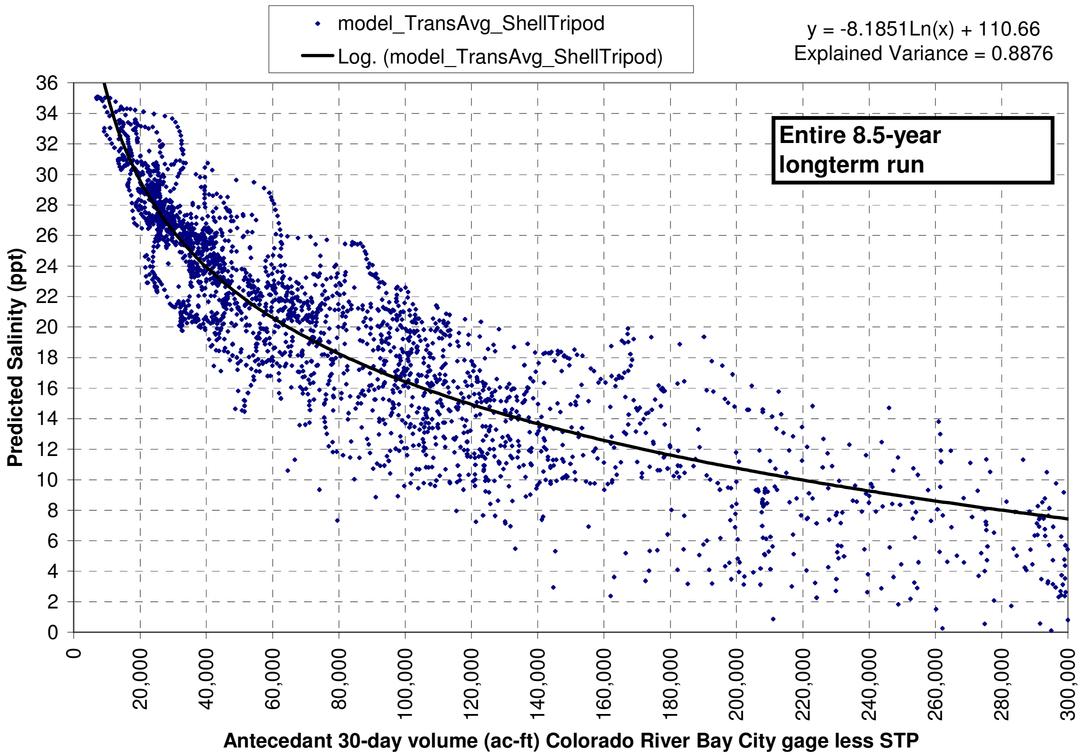


Figure 34. Delta Edge Transect, predicted salinity vs. antecedent 30-day flow (ac-ft)



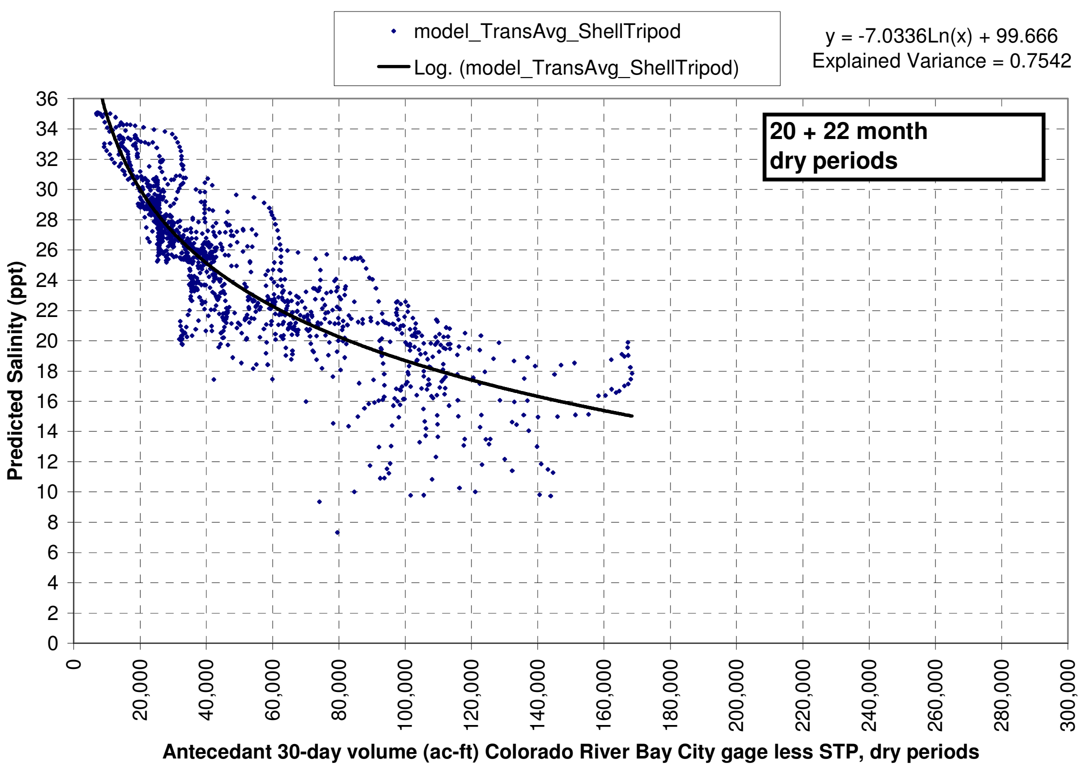
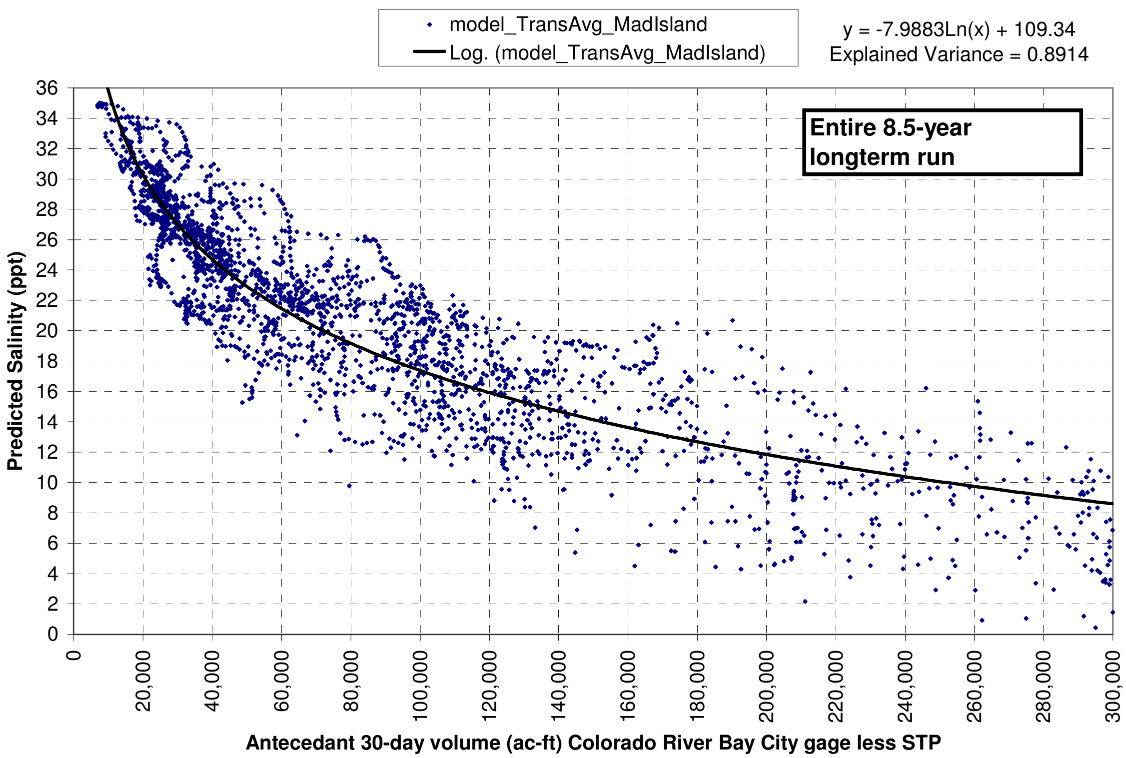


Figure 35. Shell Island/Tripod Transect, predicted salinity vs. antecedent 30-day flow (ac-ft).



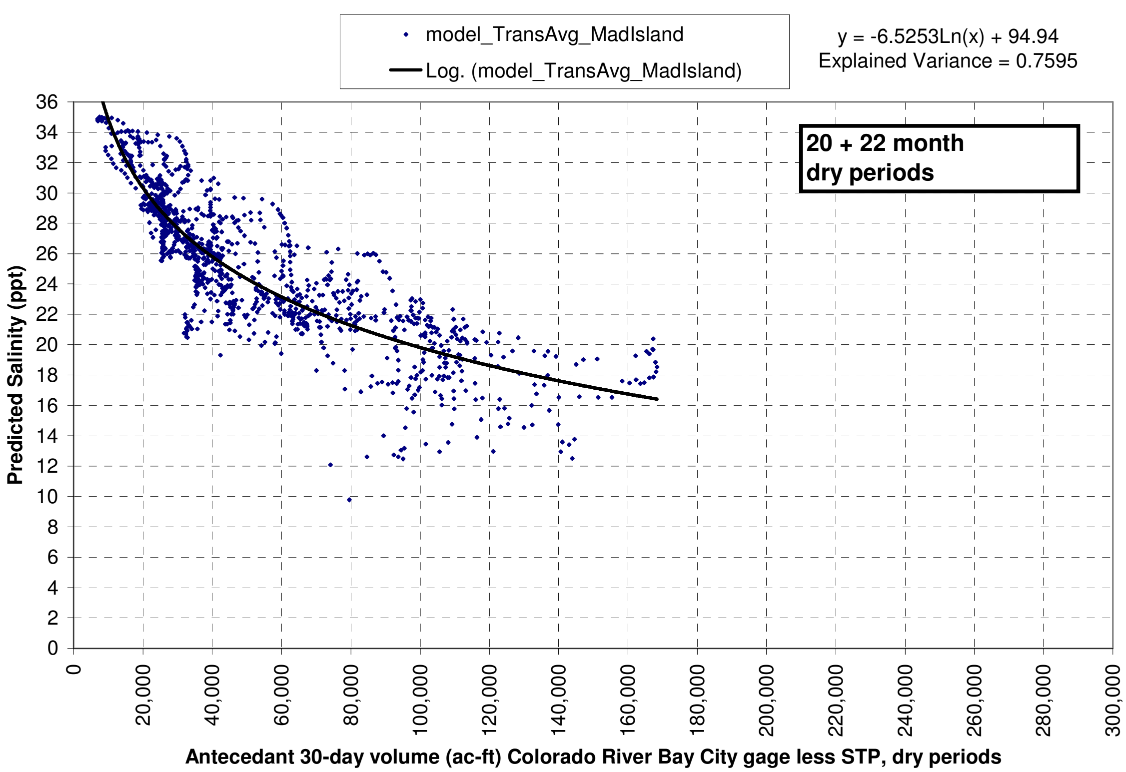


Figure 36. Mad Island Reef Transect, predicted salinity vs. antecedent 30-day flow (ac-ft).

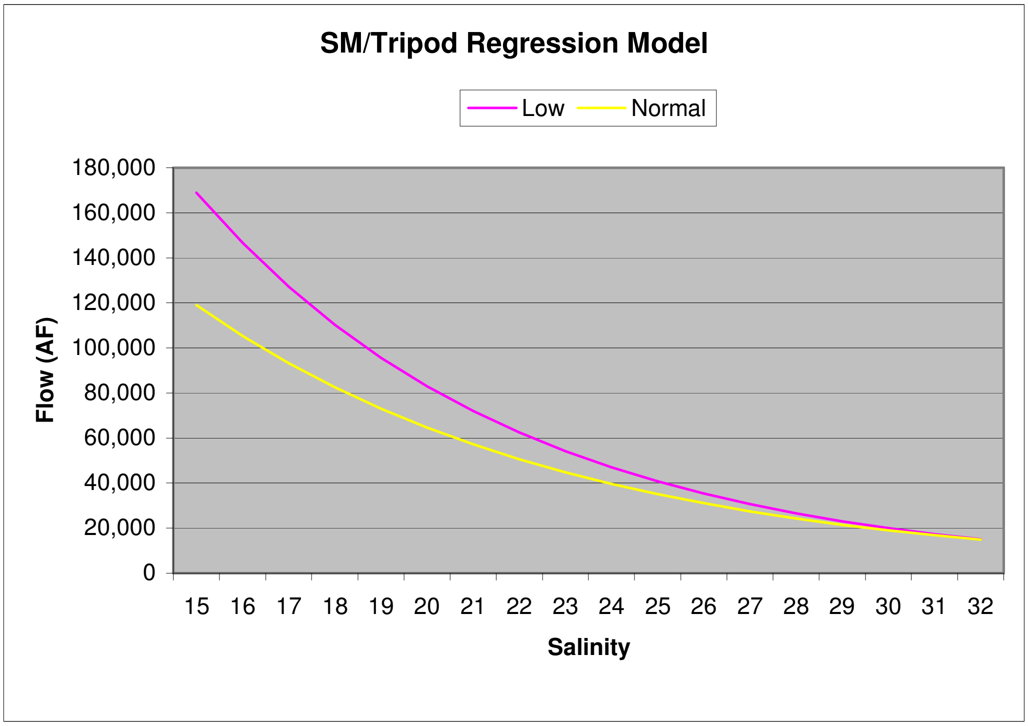


Figure 37. Low and normal flow regression equations for the SM/Tripod Transect.

Table 12. Blending the low and normal SM/Tripod regression equations.

	Flow (AF)		
Salinity (ppt)	Low Flow Eq.	Normal Eq.	
15	168,951	119,025	Apply Normal Eq.
16	146,560	105,337	I
17	127,136	93,222	I
18	110,287	82,501	I
19	95,670	73,013	I
20	82,991	64,616	I
21	71,992	57,185	Apply Normal Eq.
22	62,451	50,609	
23	54,175	44,788	
24	46,995	39,638	Linear Interpolation
25	40,767	35,079	
26	35,364	31,045	
27	30,677	27,474	Apply Low Flow Eq.
28	26,611	24,315	I
29	23,085	21,518	I
30	20,025	19,044	I
31	17,371	16,854	I
32	15,069	14,915	Apply Low Flow Eq.

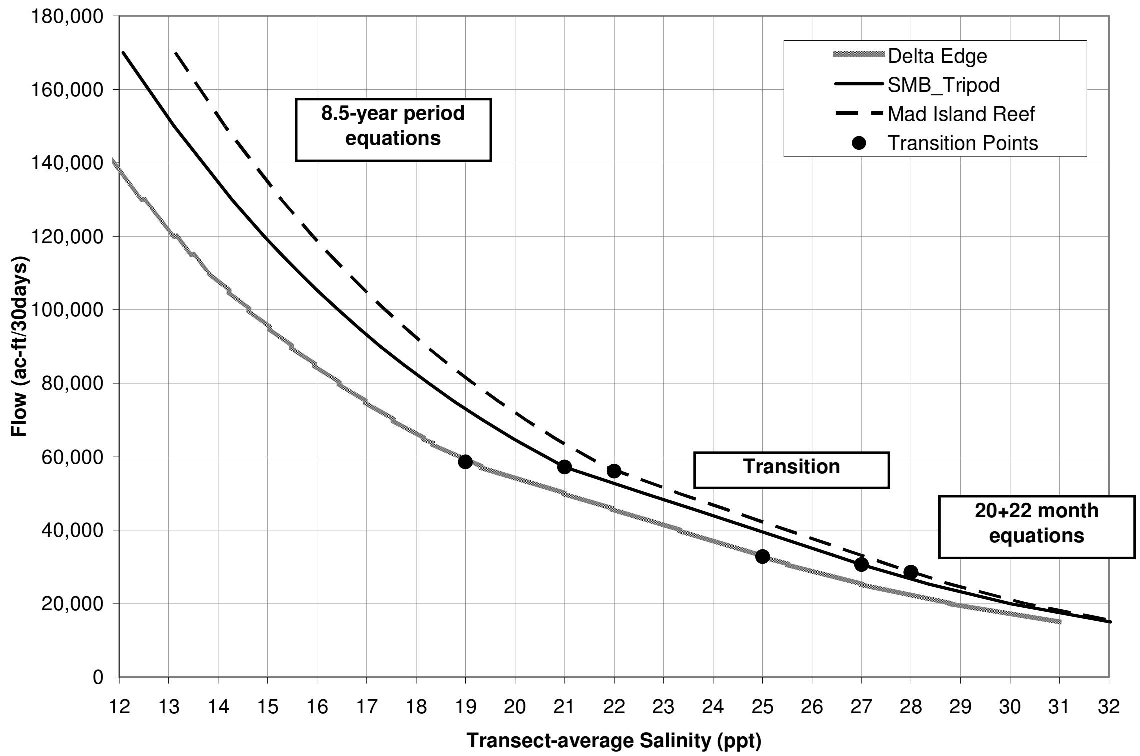


Figure 38. Blended Regression Curves

The blended regression equations for each transect can now be used to estimate the Colorado River inflow required to achieve the salinity ranges which correspond to the desired habitat conditions embodied in the MBHE inflow regime criteria. Referring to Table 11 in Section 3.3.4, the desired salinity results for the Delta Edge transect for these criteria levels are as follows:

MBHE 4	15 ppt.
MBHE 3	20 ppt,
MBHE 2	24 ppt,
MBHE 1	27 ppt,

Applying the blended Delta Edge transect regression equations, the estimated flow (rounded to nearest 1,000AF) necessary to yield these salinity values was 95,000 AF, 54,000 ac-ft, 37,000 ac-ft and 25,000 ac-ft, respectively. These flow volumes were then translated to resulting salinities at the SM/Tripod and Mad Island transects, using the aforementioned blended regression equations for each transect, yielding the flows and Design Area salinity ranges for each criteria level summarized in Table 13.

Table 13. Summary of Colorado inflows and resulting salinities in the Design Area.

Inflow Criteria	Flow (AF / 30 days)	Salinity (ppt) over Design Area		
		Delta Edge	SM/Tripod	Mad Island
MBHE 4	95,000	15.0	16.8	17.8
MBHE 3	54,000	20.1	21.7	22.4
MBHE 2	37,000	24.0	25.6	26.2
MBHE 1	25,000	27.1	28.4	28.9

5.0 Summary of Proposed Inflow Criteria and their Application

The freshwater inflow criteria are delineated in three main components of an overall inflow spectrum. The long-term flow criteria to maintain the essential food input, which sustains the historic chlorophyll-*a* levels in the bay is expressed as a long-term volume and flow variability. The four MBHE inflow regime criteria embrace monthly average flow objectives discussed in Section 4.0, seasonally adjusted for flow pulses (freshets) in both the spring and fall periods, and a guideline flow for the remaining months of the year (to be discussed in Section 5.2). For these criteria, the project team has employed the results of the habitat modeling, oyster modeling and the benthic condition analyses, supported by the hydrodynamic/salinity modeling work, to set flow values. These flow criteria embrace varying monthly average flow objectives ranging from a low of 25,000 AF per month to a high of 95,000 AF. Finally, Threshold inflow criteria would be applied during extremely low flow conditions (at or near drought-of-record), and consist of a monthly minimum flow objective and potential adaptive management opportunities (to be discussed in Section 5.3.3).

The numerical values presented in Section 4.0 provide only one component (magnitude) of the freshwater inflow criteria. The frequency, timing, and duration of these flow volumes are vital to the ecological integrity of Matagorda Bay. Each component, whether in unison, combination, or individually, if allowed to extend substantially beyond the natural tendency of the bay, can shift the ecological community and thus alter the character of the bay. The following three sections will address frequency (Achievement Guidelines), timing (Freshet Analysis), and duration (Implementation). It should be noted that although presented in individual sections these components are by no means mutually exclusive.

5.1 Achievement Guidelines

Achievement guidelines are imposed to address the frequency component of the inflow regime. The intent of both the Threshold minimum monthly flows and the Long-term Flow Volume and Variability criteria are that these criteria would be met 100% of the time. In the case of the Threshold monthly minimum, these requirements can be readily incorporated in the operational protocols implemented for the Highland Lakes (or potentially other Project-related storage), which would be the primary source for meeting these minimum flows. On the other hand, the nature of the long-term objectives requires a simulation of expected Colorado River flows based on historical hydrology in the system. This is further discussed in Section 5.4.

With respect to the varying flow levels which make up the MBHE inflow regime criteria (MBHE 1-4), it is necessary to develop a set of achievement guidelines, expressed as a percent of the time that these conditions can be expected to be met or exceeded. For this, the study team has turned to the historical frequency of occurrence of the flow levels and the related salinity ranges for guidance, under the presumption that bay existing productivity would be maintained if these historical flow and salinity levels were not substantially altered. Arguably, conditions should be improved given the existence of the Diversion Channel, which delivers more of the Colorado River flow to the bay system rather than to the Gulf of Mexico.

The primary source of data for determining the historical flow characteristics of the lower Colorado is the gage record at Bay City. Continuous daily flow volumes starting in May 1948 are available as are daily withdrawals from the river below Bay City by STP starting in 1988. Just as previously described for input to the 8.5-year hydrodynamic model simulation, the Bay City and STP daily records have been processed to provide a time series of 30-day antecedant flow volumes for the entire period of record (1949 through 2007). The frequency distribution of these results is shown in Figure 39, for the full flow range, and in Figure 40, for a truncated flow range up to 150,000 ac-ft, which shows more detail at lower flows. From this distribution of 30 day cumulative flow volumes, the historical frequency of occurrence of the MBHE inflow regime levels, that have been determined to correspond with the desired salinity ranges, are as follows:

Condition	Flow Level	Period of Record (Frequency)
MBHE 4	>95,000 AF/30 days	41%
MBHE 3	>54,000 AF/30 days	59%
MBHE 2	>37,000 AF/30 days	74%
MBHE 1	>25,000 AF/30 days	87%

Another way to assess the frequency of occurrence of the for MBHE inflow regime conditions is directly through the desired salinity ranges that correspond to the habitat conditions, although the period of salinity data collection is substantially shorter, and the construction of the Diversion Channel presents a complication. The TPWD salinity measurements taken when Otter Trawl samples are collected in the Coastal Fisheries Program have been analyzed to compute the frequency of occurrence of various salinity levels. The Otter Trawl salinities have been limited to the post-Diversion period, as the flow salinity relationship was clearly altered by that development.

The Otter Trawl sampling was selected because it represents data from the open water as opposed to the bay fringe. The TPWD data from the entire Design Area from the Mad Island to the edge of Delta transects was averaged monthly to characterize salinity conditions in the upper EAMB. The data set is rather limited, and in some cases a single measurement constitutes the monthly average. Acknowledging this shortcoming, the frequency distribution of the resulting monthly averages is shown in Figure 41.

The resulting frequency of occurrence of the salinity conditions corresponding to the four MBHE inflow regime criteria are summarized in Table 14 below.

Table 14. MBHE inflow regime criteria – salinity frequency of occurrence (post-Diversion).

	Desired Salinity Range	Test Value	TPWD Otter Trawl (post Diversion)
MBHE 4	15 – 18 ppt	<17 ppt	41%
MBHE 3	20 – 22.5 ppt	<22 ppt	61%
MBHE 2	24 – 26 ppt	< 25 ppt	76%
MBHE 1	27 – 29 ppt	< 28 ppt	84%

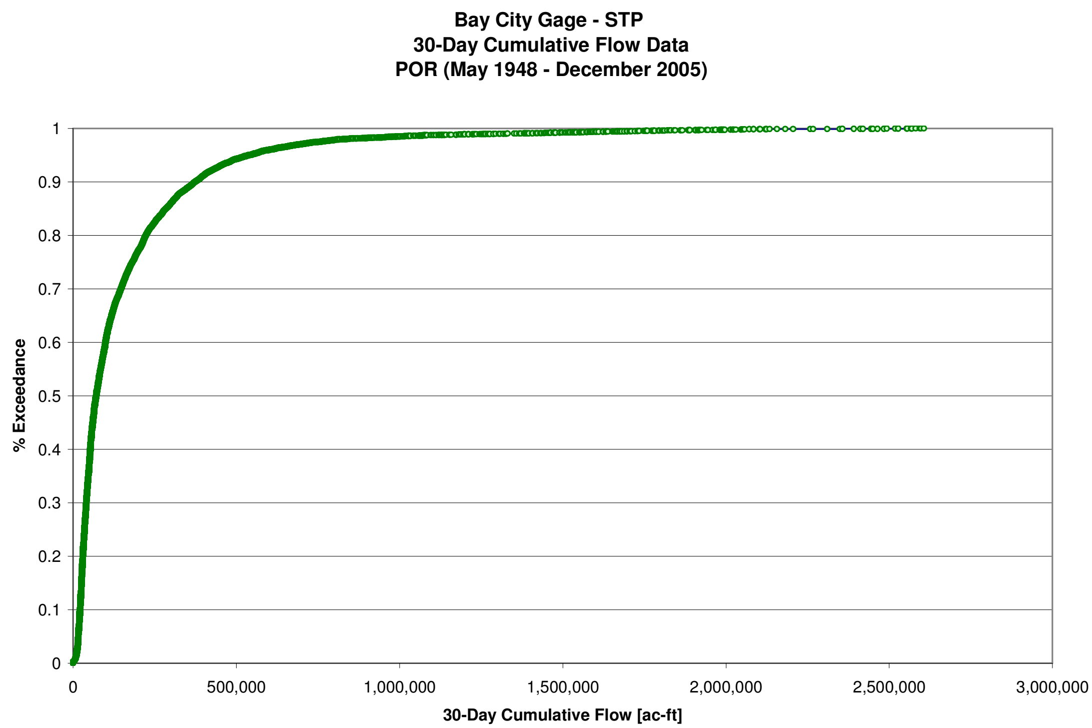


Figure 39. Period of record flow distribution (Bay City less STP Diversion – 30 day cumulative flow).

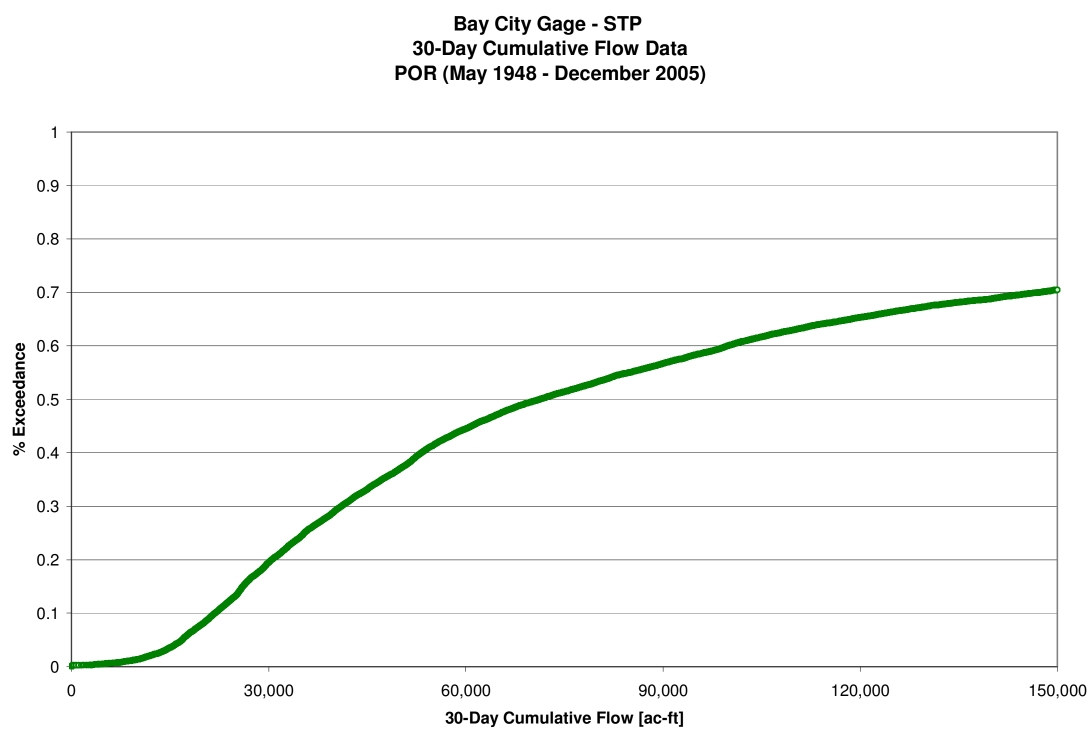


Figure 40. Flow distribution up to 150,000 ac-ft.

In each instance, the salinity value best approximating the Shell Island/Tripod transect has been chosen as the "test" value. To test the comparability of salinity frequency of occurrence and corresponding flow frequency, we have calculated the flow frequency for the period (1993-2006) that matches the period of the salinity record. These results are shown in Table 15 below.

Table 15. Comparison of Flow and Salinity Frequency of Occurrence.

	Flow	TPWD Otter Trawl
	(1993 through 2006)	
MBHE 4	43%	41%
MBHE 3	62%	61%
MBHE 2	78%	76%
MBHE 1	92%	84%

For this 14-year data set, the corresponding flow and salinity frequencies compare favorably. In fact, given the series of assumptions that had to be made for the salinity data set, this level of agreement is rather impressive.

This analysis leads to the conclusion that the alignment of MBHE inflow regime criteria with the desired salinity ranges in the Design Area are further confirmed, and that the frequency distribution of salinity and flow are comparable. This suggests that one can look to the long-term record of flow to inform the specification of appropriate achievement guidelines for the MBHE inflow regime criteria levels. Since the flow in the lower river is not impacted by the construction of the diversion, there is no need to ignore the full period of record, which encompasses 59 full calendar years and includes the DOR conditions in the early 1950s. Hence, after superimposing the seasonal pulse flow analysis presented below in Section 5.2, the recommended achievement guidelines for the MBHE inflow regime criteria will be recommended based on long-term Colorado River flow statistics.

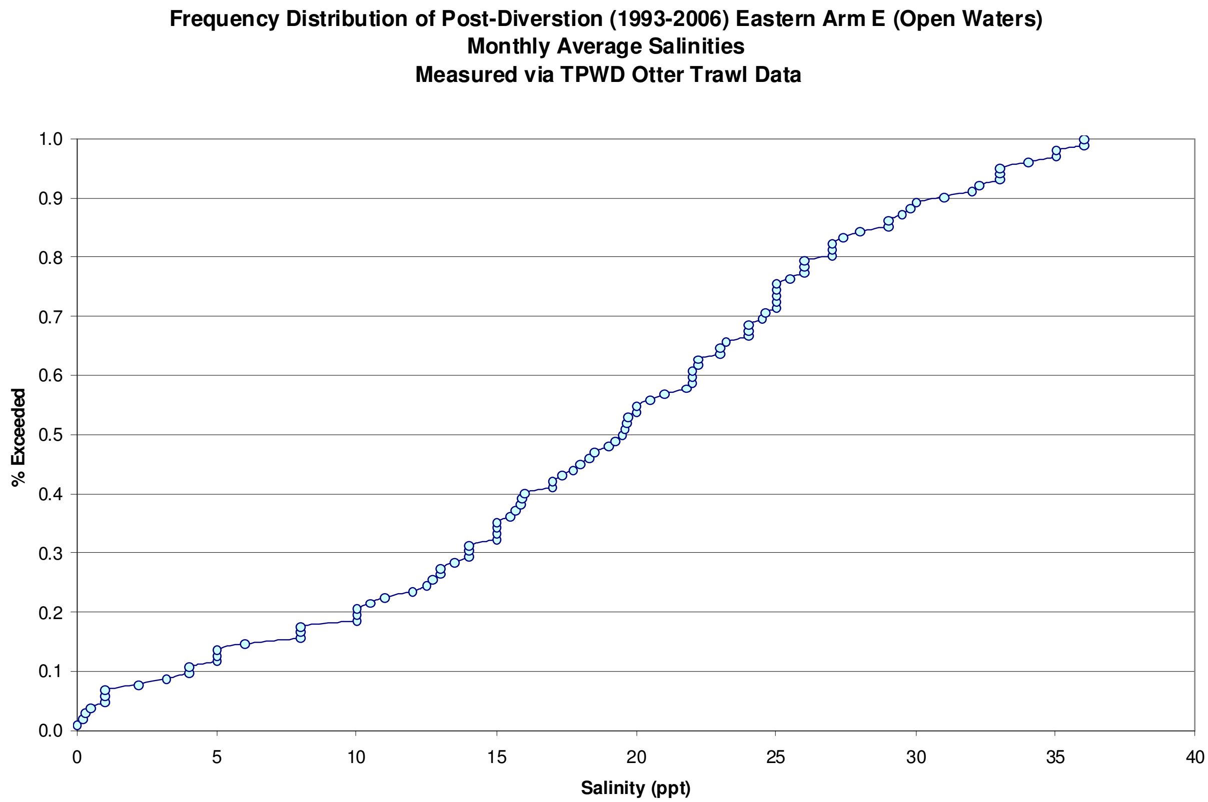


Figure 41. Frequency distribution of post-diversion TPWD Otter Trawl salinity data.

5.2 Seasonal Pulse Flow Analysis

The timing of freshwater inflow to a bay has long been acknowledged as being extremely important in maintaining the ecological productivity of the system. For ease of planning and perceived operational constraints, flow recommendations over the years have often adhered to a man-imposed calendar. However, the organisms in Matagorda Bay react less to specific calendar months, but rather are considered to be responsive to pulses of nutrients, alterations in salinity, and the suitability of habitat conditions, along with many other factors, throughout their respective life cycles. This has motivated the formalization of the concept of a hydrological seasonal pulse or "freshet" and its incorporation into the bio-statistical modeling described in Section 2.5.

The next step in specifying inflow criteria to be applied to the Colorado River is to account for this importance of pulses in inflow. Rather than prescribing fixed monthly flow objectives, it is preferable to take into account the reality that natural flows into the bay are highly variable with season, and that to finalize recommended flow volumes and achievement guidelines for the MBHE inflow regime criteria, some method of superimposing this natural variability needed to be developed. A major part of the MBHE bio-statistical analysis was to evaluate the ecological significance of pulsed flows to the key species. This analysis confirmed the importance of freshets by demonstrating that improved explained variance was achieved for inflow-sensitive species using freshet parameters as the inflow independent variable(s) compared to conventional measures of inflow (e.g., calendar-period averages).

Extensive analysis of the natural spring and fall seasonal pulses has been performed as a part of the MBHE bio-statistical work and is reported in MBHE 2006d. Various methods of describing the spring and fall pulses were developed, ranging from a simple technique for calculating the maximum flow occurring in a consecutive three-month period, to an objective mathematical method based on exceeding certain rate of change in flow, as summarized in Section 2.5. In both of these methods, a freshet is characterized by a flow magnitude (or volume in ac-ft), an onset day or month, and a duration.

In order to distribute the various MBHE inflow regime flow volumes throughout the year, the multiple freshet identification methodologies have been applied to the gage record at Bay City for the period 1949 through 2007. The data were subjected to freshet calculations based upon:

- the objective freshet identification methodology described in MBHE 2006d;
- the 3-Sub method in which the maximum three-month cumulative flow is inserted if a freshet for a given spring or fall season is not identified; and
- the results from the simplified three-month approach.

These results are shown in Tables 16 through 19. Note that the objective freshet identification methodology (Table 16) often fails to identify a pulse of flow in the spring and/or fall months when the total annual flow is very low. Because this is the condition that is of primary interest when distributing flow volumes, of note are the simplified three month results for both the full period of record (Table 18) and for only those years in which the annual flow volume is less than the period of record(POR) median inflow (Table 19). These contribution percentages are also shown in Figure 42 for the years in which the annual flow was less than the median. The seasonal flow volumes in Tables 18 and 19 are calculated as the maximum three-month flow in the spring and fall, with the remainder being assigned to the six-month intervening period.

In order to apply the freshet results in flow criteria specification, a duration needs to be determined. The statistics presented in Tables 16 and 17 show that both the freshet tool and the 3-Sub method yield average spring and fall durations greater than 60 days and less than 90 days in length. Given the monthly time step utilized in the Water Availability Model (WAM) modeling to project future flow conditions, it is necessary to select durations in whole months. Based on the flow analyses, the recommendation is to use a three-month period (Tables 18 and 19) for determining both spring and fall freshet volumes.

Finally, to avoid any overlap when calculating predicted freshet volumes, the three-month spring freshet will be defined as the maximum consecutive three-month volume occurring during the January through July period, and for the fall, between August and December. This corresponds to a spring onset from January through May and a fall onset of August through October.

Table 16. Bay City freshets from objective method.

	Freshet					Freshet				
		Spring		Jan-Dec	Percent		Fall		Jan-Dec	Percent
	Onset	Magnitude	Duration	Annual	of Annual	Onset	Magnitude	Duration	Annual	of Annual
Year	[Julian Day]	[ac-ft]	[Days]	[ac-ft]	Total	[Julian Day]	[ac-ft]	[Days]	[ac-ft]	Total
1949	22	762,651	133	1,531,747	49.8%	273	357,211	55	1,531,747	23.3%
1950				1,135,787					1,135,787	
1951	152	89,857	41	465,442	19.3%	247	108,077	54	465,442	23.2%
1952	143	128,458	35	537,129	23.9%	329	188,614	46	537,129	35.1%
1953	113	329,167	57	974,936	33.8%	238	133,736	38	974,936	13.7%
1954				310,482					310,482	
1955	31	391,577	113	977,276	40.1%				977,276	
1956				343,234					343,234	
1957	123	3,135,431	74	5,957,151	52.6%	267	1,489,428	67	5,957,151	25.0%
1958				3,174,238					3,174,238	
1959	98	564,972	46	2,710,104	20.8%	277	905,574	49	2,710,104	33.4%
1960	174	631,299	41	3,187,101	19.8%	281	721,091	59	3,187,101	22.6%
1961	165	932,628	46	3,812,807	24.5%	250	704,886	44	3,812,807	18.5%
1962				670,466					670,466	
1963				397,696					397,696	
1964				334,168					334,168	
1965	20	1,291,250	166	1,882,366	68.6%	291	577,309	94	1,882,366	30.7%
1966	117	510,153	57	1,090,820	46.8%				1,090,820	
1967				477,424		241	221,032	57	477,424	46.3%
1968	14	870,783	49	3,604,257	24.2%	331	185,972	45	3,604,257	5.2%
1969	46	1,083,465	129	1,683,885	64.3%	293	1,518,744	186	1,683,885	90.2%
1970				2,383,801		274	271,454	57	2,383,801	11.4%
1971				978,293		248	853,736	136	978,293	87.3%
1972	125	285,187	42	833,745	34.2%				833,745	
1973	15	1,425,660	167	2,639,494	54.0%	281	666,292	49	2,639,494	25.2%
1974	17	406,889	44	2,771,308	14.7%	248	1,776,793	113	2,771,308	64.1%
1975	139	1,303,498	52	3,023,090	43.1%				3,023,090	
1976	98	548,001	63	1,874,868	29.2%				1,874,868	
1977	-20	1,574,340	89	2,240,198	70.3%				2,240,198	
1978				665,127		250	177,279	42	665,127	26.7%
1979	-2	1,081,384	93	2,157,445	50.1%	259	235,384	43	2,157,445	10.9%
1980	17	341,998	90	726,706	47.1%				726,706	
1981	69	1,592,624	146	2,727,350	58.4%	300	545,395	47	2,727,350	20.0%
1982	111	550,903	60	1,192,602	46.2%				1,192,602	
1983	44	417,314	75	1,212,958	34.4%	254	226,600	47	1,212,958	18.7%
1984	57	437,699	64	741,465	59.0%	290	332,043	41	741,465	44.8%
1985				1,435,855		321	358,263	46	1,435,855	25.0%
1986	132	443,070	75	2,101,033	21.1%	286	1,664,628	113	2,101,033	79.2%
1987	155	1,974,050	51	4,059,703	48.6%				4,059,703	
1988	69	170,620	51	522,446	32.7%				522,446	
1989	8	143,419	56	532,802	26.9%				532,802	
1990				404,100					404,100	
1991	9	1,018,493	91	2,497,966	40.8%				2,497,966	
1992	-10	8,777,731	157	9,609,917	91.3%				9,609,917	
1993				2,241,362					2,241,362	
1994	127	220,140	56	1,504,193	14.6%	285	688,562	44	1,504,193	45.8%
1995	68	978,387	84	1,676,969	58.3%				1,676,969	
1996	152	153,810	56	642,409	23.9%	235	204,149	45	642,409	31.8%
1997	53	2,527,300	110	4,635,372	54.5%	264	446,723	58	4,635,372	9.6%
1998	49	867,384	81	3,482,487	24.9%	286	1,700,186	47	3,482,487	48.8%
1999				881,659					881,659	
2000				782,506		301	347,407	56	782,506	44.4%
2001				2,090,741		239	1,074,397	121	2,090,741	51.4%
2002				2,734,899		188	1,487,921	82	2,734,899	54.4%
2003	52	654,169	47	1,571,292	41.6%				1,571,292	
2004	16	1,144,445	117	3,516,708	32.5%	204	1,698,030	47	3,516,708	48.3%
2005				1,626,139					1,626,139	
Average	73	1,046,321	79	1,929,430	40.6%	269	705,384	65	1,929,430	36.0%
Post 92	74	935,090	79	2,106,672	35.8%	250	955,922	63	2,106,672	41.8%
Pre 92	75	814,561	77	1,697,229	40.0%	275	618,241	66	1,697,229	33.9%
Median	63	642,734	64	1,571,292	40.4%	273	545,395	49	1,571,292	30.7%
Post 92	53	867,384	81	1,676,969	32.5%	252	881,479	52	1,676,969	47.0%
Pre 92	69	557,938	62	1,212,958	40.4%	274	358,263	49	1,212,958	25.0%

Table 17. Bay City freshets from 3-Sub method.

	3 - SUB					3 - SUB				
Year	Onset [Julian Day	Spring Magnitude [ac-ft]	Duration [Days]	Jan-Dec Annual [ac-ft]	Percent of Annual Total	Onset [Julian Day	Fall Magnitude [ac-ft]	Duration [Days]	Jan-Dec Annual [ac-ft]	Percent of Annual Total
1949	22	762,651	133	1,531,747	49.8%	273	357,211	55	1,531,747	23.3%
1950	91	457,168	90	1,135,787	40.3%	244	163,765	90	1,135,787	14.4%
1951	152	89,857	41	465,442	19.3%	247	108,077	54	465,442	23.2%
1952	143	128,458	35	537,129	23.9%	329	188,614	46	537,129	35.1%
1953	113	329,167	57	974,936	33.8%	238	133,736	38	974,936	13.7%
1954	1	86,604	90	310,482	27.9%	213	89,615	90	310,482	28.9%
1955	31	391,577	113	977,276	40.1%	244	324,730	90	977,276	33.2%
1956	91	131,076	90	343,234	38.2%	213	58,818	90	343,234	17.1%
1957	123	3,135,431	74	5,957,151	52.6%	267	1,489,428	67	5,957,151	25.0%
1958	1	1,391,702	90	3,174,238	43.8%	182	564,040	90	3,174,238	17.8%
1959	98	564,972	46	2,710,104	20.8%	277	905,574	49	2,710,104	33.4%
1960	174	631,299	41	3,187,101	19.8%	281	721,091	59	3,187,101	22.6%
1961	165	932,628	46	3,812,807	24.5%	250	704,886	44	3,812,807	18.5%
1962	1	266,071	90	670,466	39.7%	274	174,006	90	670,466	26.0%
1963	1	186,611	90	397,696	46.9%	182	81,723	90	397,696	20.5%
1964	1	92,765	90	334,168	27.8%	244	140,671	90	334,168	42.1%
1965	20	1,291,250	166	1,882,366	68.6%	291	577,309	94	1,882,366	30.7%
1966	117	510,153	57	1,090,820	46.8%	274	105,017	90	1,090,820	9.6%
1967	91	64,608	90	477,424	13.5%	241	221,032	57	477,424	46.3%
1968	14	870,783	49	3,604,257	24.2%	331	185,972	45	3,604,257	5.2%
1969	46	1,083,465	129	1,683,885	64.3%	293	1,518,744	186	1,683,885	90.2%
1970	60	1,207,700	90	2,383,801	50.7%	274	271,454	57	2,383,801	11.4%
1971	60	83,443	90	978,293	8.5%	248	853,736	136	978,293	87.3%
1972	125	285,187	42	833,745	34.2%	274	130,691	90	833,745	15.7%
1973	15	1,425,660	167	2,639,494	54.0%	281	666,292	49	2,639,494	25.2%
1974	17	406,889	44	2,771,308	14.7%	248	1,776,793	113	2,771,308	64.1%
1975	139	1,303,498	52	3,023,090	43.1%	182	405,669	90	3,023,090	13.4%
1976	98	548,001	63	1,874,868	29.2%	274	752,204	90	1,874,868	40.1%
1977	-20	1,574,340	89	2,240,198	70.3%	182	141,675	90	2,240,198	6.3%
1978	1	151,468	90	665,127	22.8%	250	177,279	42	665,127	26.7%
1979	-2	1,081,384	93	2,157,445	50.1%	259	235,384	43	2,157,445	10.9%
1980	17	341,998	90	726,706	47.1%	274	145,936	90	726,706	20.1%
1981	69	1,592,624	146	2,727,350	58.4%	300	545,395	47	2,727,350	20.0%
1982	111	550,903	60	1,192,602	46.2%	182	211,267	90	1,192,602	17.7%
1983	44	417,314	75	1,212,958	34.4%	254	226,600	47	1,212,958	18.7%
1984	57	437,699	64	741,465	59.0%	290	332,043	41	741,465	44.8%
1985	32	514,967	90	1,435,855	35.9%	321	358,263	46	1,435,855	25.0%
1986	132	443,070	75	2,101,033	21.1%	286	1,664,628	113	2,101,033	79.2%
1987	155	1,974,050	51	4,059,703	48.6%	182	548,868	90	4,059,703	13.5%
1988	69	170,620	51	522,446	32.7%	213	108,875	90	522,446	20.8%
1989	8	143,419	56	532,802	26.9%	182	80,563	90	532,802	15.1%
1990	60	176,588	90	404,100	43.7%	182	88,929	90	404,100	22.0%
1991	9	1,018,493	91	2,497,966	40.8%	274	1,079,532	90	2,497,966	43.2%
1992	-10	8,777,731	157	9,609,917	91.3%	274	333,394	90	9,609,917	3.5%
1993	91	1,138,211	90	2,241,362	50.8%	244	181,438	90	2,241,362	8.1%
1994	127	220,140	56	1,504,193	14.6%	285	688,562	44	1,504,193	45.8%
1995	68	978,387	84	1,676,969	58.3%	274	190,241	90	1,676,969	11.3%
1996	152	153,810	56	642,409	23.9%	235	204,149	45	642,409	31.8%
1997	53	2,527,300	110	4,635,372	54.5%	264	446,723	58	4,635,372	9.6%
1998	49	867,384	81	3,482,487	24.9%	286	1,700,186	47	3,482,487	48.8%
1999	1	383,599	90	881,659	43.5%	182	126,343	90	881,659	14.3%
2000	91	198,182	90	782,506	25.3%	301	347,407	56	782,506	44.4%
2001	1	706,929	90	2,090,741	33.8%	239	1,074,397	121	2,090,741	51.4%
2002	152	946,233	90	2,734,899	34.6%	188	1,487,921	82	2,734,899	54.4%
2003	52	654,169	47	1,571,292	41.6%	182	268,284	90	1,571,292	17.1%
2004	16	1,144,445	117	3,516,708	32.5%	204	1,698,030	47	3,516,708	48.3%
2005	1	998,479	90	1,626,139	61.4%	182	169,517	90	1,626,139	10.4%
Average	63	858,642	83	1,929,430	39.1%	248	500,574	77	1,929,430	28.4%
Post 92	66	839,790	84	2,106,672	38.5%	236	660,246	73	2,106,672	30.4%
Pre 92	64	680,177	81	1,697,229	38.1%	251	456,189	77	1,697,229	28.3%
Median	57	548,001	90	1,571,292	39.7%	250	271,454	90	1,571,292	22.6%
Post 92	53	867,384	90	1,676,969	34.6%	239	347,407	82	1,676,969	31.8%
Pre 92	60	457,168	90	1,212,958	39.7%	254	235,384	90	1,212,958	22.6%

Table 18. Seasonal flow distribution (three-month method) – Bay City less STP.

Year	Annual Flow	**Maximum Spring**	Percent	**Maximum Fall**	Percent	**Intervening**	Percent
1949	1,531,747	645,055	42.1%	530,047	34.6%	356,646	23.3%
1950	1,135,787	457,168	40.3%	163,765	14.4%	514,854	45.3%
1951	465,442	142,286	30.6%	141,880	30.5%	181,276	38.9%
1952	537,129	197,786	36.8%	180,303	33.6%	159,039	29.6%
1953	974,936	373,930	38.4%	233,389	23.9%	367,616	37.7%
1954	310,482	86,604	27.9%	89,615	28.9%	134,263	43.2%
1955	977,276	337,196	34.5%	324,730	33.2%	315,350	32.3%
1956	343,234	131,076	38.2%	58,818	17.1%	153,340	44.7%
1957	5,957,151	3,466,861	58.2%	1,676,807	28.1%	813,483	13.7%
1958	3,174,238	1,391,702	43.8%	524,846	16.5%	1,257,689	39.6%
1959	2,710,104	737,078	27.2%	1,268,926	46.8%	704,100	26.0%
1960	3,187,101	1,120,661	35.2%	952,007	29.9%	1,114,433	35.0%
1961	3,812,807	1,099,855	28.8%	1,051,140	27.6%	1,661,812	43.6%
1962	670,466	266,071	39.7%	174,006	26.0%	230,390	34.4%
1963	397,696	186,611	46.9%	64,255	16.2%	146,830	36.9%
1964	334,168	92,765	27.8%	140,671	42.1%	100,732	30.1%
1965	1,882,366	847,172	45.0%	520,869	27.7%	514,324	27.3%
1966	1,090,820	625,488	57.3%	105,017	9.6%	360,315	33.0%
1967	477,424	64,608	13.5%	305,910	64.1%	106,907	22.4%
1968	3,604,257	1,747,894	48.5%	235,271	6.5%	1,621,091	45.0%
1969	1,683,885	828,518	49.2%	470,872	28.0%	384,495	22.8%
1970	2,383,801	1,207,700	50.7%	368,144	15.4%	807,957	33.9%
1971	978,293	83,443	8.5%	609,779	62.3%	285,071	29.1%
1972	833,745	386,411	46.3%	130,691	15.7%	316,643	38.0%
1973	2,639,494	984,670	37.3%	880,288	33.4%	774,536	29.3%
1974	2,771,308	575,455	20.8%	1,528,701	55.2%	667,152	24.1%
1975	3,023,090	1,679,326	55.5%	188,097	6.2%	1,155,667	38.2%
1976	1,874,868	631,325	33.7%	752,204	40.1%	491,340	26.2%
1977	2,240,198	1,442,594	64.4%	137,800	6.2%	659,804	29.5%
1978	665,127	151,468	22.8%	268,871	40.4%	244,788	36.8%
1979	2,157,445	1,028,598	47.7%	325,890	15.1%	802,957	37.2%
1980	718,786	293,146	40.8%	145,936	20.3%	279,704	38.9%
1981	2,727,350	1,389,671	51.0%	858,833	31.5%	478,846	17.6%
1982	1,192,602	639,045	53.6%	147,913	12.4%	405,644	34.0%
1983	1,186,910	445,991	37.6%	287,219	24.2%	453,700	38.2%
1984	733,898	114,612	15.6%	448,759	61.1%	170,528	23.2%
1985	1,380,092	514,967	37.3%	470,913	34.1%	394,212	28.6%
1986	2,097,044	476,443	22.7%	1,242,894	59.3%	377,707	18.0%
1987	4,059,703	2,272,661	56.0%	323,665	8.0%	1,463,377	36.0%
1988	474,831	200,071	42.1%	108,875	22.9%	165,885	34.9%
1989	484,315	181,142	37.4%	60,196	12.4%	242,977	50.2%
1990	368,458	145,295	39.4%	79,725	21.6%	143,438	38.9%
1991	2,463,006	648,530	26.3%	1,063,746	43.2%	750,729	30.5%
1992	9,603,040	5,590,994	58.2%	333,394	3.5%	3,678,653	38.3%
1993	2,241,362	1,138,211	50.8%	181,438	8.1%	921,713	41.1%
1994	1,462,691	275,007	18.8%	924,519	63.2%	263,165	18.0%
1995	1,671,278	818,884	49.0%	188,342	11.3%	664,051	39.7%
1996	595,134	153,238	25.7%	226,040	38.0%	215,855	36.3%
1997	4,569,739	2,183,537	47.8%	540,480	11.8%	1,845,721	40.4%
1998	3,443,368	941,248	27.3%	2,037,002	59.2%	465,118	13.5%
1999	858,043	371,541	43.3%	97,198	11.3%	389,303	45.4%
2000	716,558	176,823	24.7%	403,997	56.4%	135,738	18.9%
2001	2,028,486	688,895	34.0%	740,299	36.5%	599,293	29.5%
2002	2,692,731	830,954	30.9%	1,229,351	45.7%	632,426	23.5%
2003	1,571,292	948,000	60.3%	221,526	14.1%	401,766	25.6%
2004	3,454,334	1,088,446	31.5%	1,855,929	53.7%	509,960	14.8%
2005	1,620,445	998,479	61.6%	142,003	8.8%	479,962	29.6%
2006	498,896	156,037	31.3%	166,653	33.4%	176,206	35.3%
2007	3,724,079	2,128,338	57.2%	665,905	17.9%	929,836	25.0%
Mean	1,923,125	827,586	39.1%	501,633	28.8%	593,905	32.1%
Median	1,571,292	631,325	38.4%	323,665	27.7%	405,644	33.9%
Stan. Dev.	1,617,336	914,821	13.0%	480,106	17.1%	578,003	8.8%

Table 19. Seasonal flow distribution (three-month method) – Annual flows less than POR median.

Year	Annual Flow	**Maximum Spring**	Percent	**Maximum Fall**	Percent	**Intervening**	Percent
1949	1,531,747	645,055	42.1%	530,047	34.6%	356,646	23.3%
1950	1,135,787	457,168	40.3%	163,765	14.4%	514,854	45.3%
1951	465,442	142,286	30.6%	141,880	30.5%	181,276	38.9%
1952	537,129	197,786	36.8%	180,303	33.6%	159,039	29.6%
1953	974,936	373,930	38.4%	233,389	23.9%	367,616	37.7%
1954	310,482	86,604	27.9%	89,615	28.9%	134,263	43.2%
1955	977,276	337,196	34.5%	324,730	33.2%	315,350	32.3%
1956	343,234	131,076	38.2%	58,818	17.1%	153,340	44.7%
1962	670,466	266,071	39.7%	174,006	26.0%	230,390	34.4%
1963	397,696	186,611	46.9%	64,255	16.2%	146,830	36.9%
1964	334,168	92,765	27.8%	140,671	42.1%	100,732	30.1%
1966	1,090,820	625,488	57.3%	105,017	9.6%	360,315	33.0%
1967	477,424	64,608	13.5%	305,910	64.1%	106,907	22.4%
1971	978,293	83,443	8.5%	609,779	62.3%	285,071	29.1%
1972	833,745	386,411	46.3%	130,691	15.7%	316,643	38.0%
1978	665,127	151,468	22.8%	268,871	40.4%	244,788	36.8%
1980	718,786	293,146	40.8%	145,936	20.3%	279,704	38.9%
1982	1,192,602	639,045	53.6%	147,913	12.4%	405,644	34.0%
1983	1,186,910	445,991	37.6%	287,219	24.2%	453,700	38.2%
1984	733,898	114,612	15.6%	448,759	61.1%	170,528	23.2%
1985	1,380,092	514,967	37.3%	470,913	34.1%	394,212	28.6%
1988	474,831	200,071	42.1%	108,875	22.9%	165,885	34.9%
1989	484,315	181,142	37.4%	60,196	12.4%	242,977	50.2%
1990	368,458	145,295	39.4%	79,725	21.6%	143,438	38.9%
1994	1,462,691	275,007	18.8%	924,519	63.2%	263,165	18.0%
1996	595,134	153,238	25.7%	226,040	38.0%	215,855	36.3%
1999	858,043	371,541	43.3%	97,198	11.3%	389,303	45.4%
2000	716,558	176,823	24.7%	403,997	56.4%	135,738	18.9%
2003	1,571,292	948,000	60.3%	221,526	14.1%	401,766	25.6%
2006	498,896	156,037	31.3%	166,653	33.4%	176,206	35.3%
Mean	798,876	294,763	35.3%	243,707	30.6%	260,406	34.1%
Median	717,672	198,929	37.5%	170,330	27.4%	243,883	35.1%
Stan. Dev.	380,327	211,883	12.2%	194,406	16.7%	114,205	8.0%

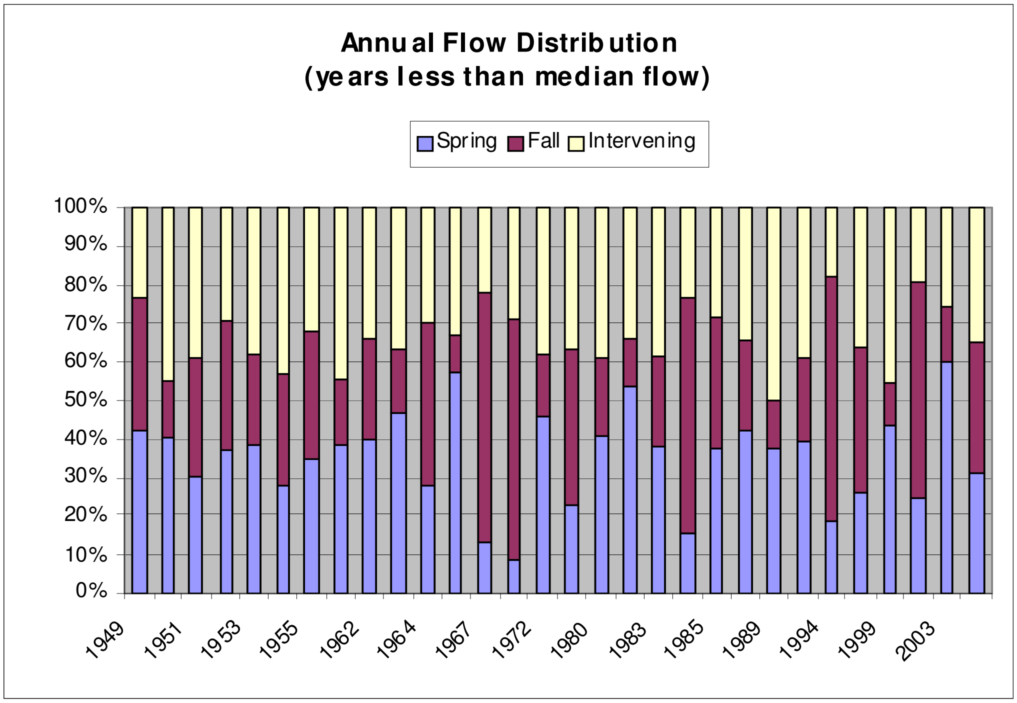


Figure 42. Distribution of seasonal flows for years having flow below the POR median.

Table 20 summarizes the median percentage of annual flow represented by the spring and the fall freshet for the four methods described above.

Table 20. Median spring and fall percentage of freshet, relative to total flow.

	Spring	Fall
Freshet tool	40.4	30.7
3 – Sub	39.7	22.6
Three month (POR)	38.4	27.7
Three month (< median)	37.5	27.4

These results show a very consistent pattern in the spring, with a somewhat higher variation in the fall. Because our interest is to distribute flows which are generally less than median flows, it would appear appropriate to focus more on the last set of statistics. Hence, the recommended seasonal distribution for development of the inflow criteria is 38% of the annualized recommended criteria in the spring period, 27% in the fall period, and the remaining 35% in the intervening six months.

Applying this seasonal distribution result to the flow volumes determined in Section 4 as required to achieve the MBHE inflow regime habitat/salinity conditions in the Design Area, yields the final recommendations for Colorado River inflow regime criteria. Table 21 below summarizes these results.

Table 21. Seasonal components of MBHE inflow regime criteria in ac-ft.

Inflow Criteria	Flow		Seasonal		
	AF / 30 days	Annualized	Spring (38%)	Fall (27%)	Intervening (35%)
MBHE 4	95,000	1,140,000	433,200	307,800	399,000
MBHE 3	54,000	648,000	246,200	175,000	226,800
MBHE 2	37,000	444,000	168,700	119,900	155,400
MBHE 1	25,000	300,000	114,000	81,000	105,000

As concluded in Section 5.1, we have determined that maintenance of the frequency of occurrence of flow volumes can be used as a measure of maintaining bay health and productivity for MBHE inflow regime flows. Using the assumptions for seasonal flow timing discussed above, we have evaluated the historical monthly flow records to determine the frequency with which **all** of the seasonal components of the above criteria (Table 21) are met or exceeded in the same year. These results have then been used to establish recommendations for the frequency that each of the specific criteria levels should be achieved. The frequency of occurrence and corresponding recommendation for achievement guideline for each of the inflow criteria are summarized in Table 22. For example, the three-month spring, three-month fall, and the six-month intervening seasonal flow volumes (168,700, 119,900 and 155,400AF, respectively), which make up the MBHE 2 criteria, should be simultaneously met or exceeded approximately 75% of the time.

Table 22. Recommended achievement guidelines.

	POR Occurrence	Recommended Achievement Guideline
Long-term Volume and Variability		100%
MBHE 4	35%	35%
MBHE 3	58%	60%
MBHE 2	72%	75%
MBHE 1	86%	90%
Threshold		100%

The recommended achievement guidelines for the MBHE 1-4 inflow criteria are intended to mimic long-term frequencies of occurrence. The goal of the minimum category is to not fall below the threshold inflow levels; hence, the achievement guideline is set at 100%. As discussed in section 3.3.1, the long-term flow category expressed as a long-term average and variability is also to be maintained. It is important to note that all of the recommended achievement guidelines require passage of time to assess success or failure. As such, all criteria will be assessed by WAM modeling as discussed in Section 5.4.

During the analysis of historical flow patterns, it became obvious that the inter- and intra-annual variability was large, and the magnitude of this variability greatly increased as median annual inflows were approached and exceeded. In developing a system operations protocol to meet the various recommended achievement guidelines, it is appropriate to take this natural variability at higher flows into account. This becomes particularly pertinent when determining whether or not the MBHE 4 achievement guideline of 35% is being met.

An example WAM run (using the 59 year historical record) that meets Threshold, and MBHE 1, 2, and 3 by employing operational constraints on the system, yielded the following result for one year of the simulation:

	WAM	MBHE 4 Criteria
Spring pulse	1,953,179	433,200
Fall pulse	184,270	307,800
Intervening	934,367	399,000
Total	3,071,816	1,140,000

In this example, the spring pulse and the intervening MBHE 4 seasonal criteria are substantially exceeded, but the fall pulse is short by 123,530 AF (or ~41,000 AF a month) during a year that received nearly 3.1 MAF in total annual inflow. For these instances, it does not seem practical to implement operational constraints to force this additional release during these extremely wet years. As discussed, the 35% achievement guideline for MBHE 4 is based on historical frequency of occurrence. However, due to this variability at higher flows, a modified application of the MBHE 4 achievement guideline is recommended.

It is recommended that WAM results be examined to determine that the 35% is achieved by a combination of years that either 1) fully satisfy all seasonal components of the MBHE 4 criteria, or 2) are projected to have an annual flow that exceeds the volume (approximately 1.6 million acre feet [MAF]) necessary to maintain a monthly average of 15 ppt salinity at the Mad Island reef transect (the outermost transect of the Design Area), meet two of the three seasonal components of MBHE 4, and exceed the MBHE 3 criteria for the remaining seasonal component. The second factor requires that all three conditions be met. The 1.6 MAF was established as the annual flow necessary (if distributed monthly ~133,000 AF) to maintain "Selected" habitat conditions throughout the entire MBHE Design Area. This flow level would result in salinities of ~15ppt at the Mad Island Transect, ~14ppt at the Shell Island/Tripod Transect, and ~12ppt at the Delta Edge Transect. Distributed with the MBHE seasonal distributions of spring, fall, and intervening, "Selected" habitat would be achieved throughout the MBHE Design Area during the spring and fall pulses, and "Good" or "Selected" habitat conditions would be present throughout the entire MBHE Design Area during the intervening period.

For a given year, if all three seasonal MBHE 4 components are not met and 1.6 MAF is not projected in the WAM run, then that year cannot be counted towards meeting the 35% achievement guideline. However, if former is not met, but the 1.6 MAF is, then an evaluation of whether two of the three MBHE 4 criteria were met is the next check. Should this fail, then that year cannot be counted toward meeting the 35% achievement guideline. However, if both the 1.6 MAF and two of the three seasonal MBHE 4 criteria are met, the final test is whether the remaining season meets MBHE 3 criteria. Again, if this test fails, then that year cannot be counted in meeting the 35% achievement guideline. For the example above, the total annual inflow was greater than 1.6 MAF, Spring and Intervening MBHE 4 criteria were met, and the 184,270 AF was greater than the 175,000 AF required for the fall MBHE 3 pulse. Therefore, in this example, the year counts towards meeting the achievement guideline for MBHE 4.

5.3 Summary of Recommended Inflow Criteria

5.3.1 Long-term Volume and Variability

The recommended long-term inflow category is made up of a long-term flow volume and flow variability criteria based on maintaining adequate nutrient loading to the Matagorda Bay system. An inflow volume of 1,300,000 ac-ft/year to the EAMB or approximately 1,400,000 to 1,500,000 ac-ft/year in the river is selected to represent maintenance of "normal" flow conditions in order to maintain the average chlorophyll-*a*. This average flow value is somewhat lower than the amount needed to meet the average post-diversion chlorophyll-*a* (1,546,000), but is higher than the amount needed taking into account the expected range of the data (1,273,000). As shown in Figure 30 (Section 3.3.1), the 1,300,000 ac-ft/year value is reasonably similar to the post-diversion condition and considerably higher than the pre-diversion flows to the EAMB. To assure that this long-term average flow is effective and continues to include the required high flow periods, it should be accompanied by a monthly CV of 0.8, a lower bound typical for the post-diversion period, and a value rarely exceeded in the pre-diversion years.

It should be emphasized that the proposed mean inflow and monthly CV values are intended to be long-term averages which have the goal of maintaining health and productivity of the system. The objective is to establish long-term flow criteria (both volume and pattern), which achieve a goal of maintaining the historical levels of bay productivity and primary productivity, as represented by chlorophyll-*a*. This presumes that there is a direct relationship between inorganic-N and organic matter carried by inflows and bay chlorophyll-*a*, and that there is a critical tie between flow variability and system productivity. Both of these presumptions are supported by the nutrient data analysis and modeling presented in MBHE 2007c.

Section 3.3.1 presents several estimates of the flow volume which could be employed. It is also clear that something like the historical level of flow variability will be needed in the future to maintain the system in its current condition. The conclusion from the nutrient loading analysis is a long-term average flow of 1.4 to 1.5 million ac-ft annually, and a CV exceeding 0.8 as the long-term inflow criteria recommendation.

5.3.2 MBHE Inflow Regime Criteria

Using the salinity-to-inflow relationships described in the Section 3.3, and the recommended salinity regimes to meet trophic level habitat conditions (Table 11), monthly average inflows of 25,000 ac-ft (MBHE 1), 37,000 ac-ft (MBHE 2), 54,000 ac-ft (MBHE 3), and 95,000 ac-ft (MBHE 4) are proposed. These flow volumes constitute the estimated flows necessary to achieve the habitat conditions summarized in Table 11.

The proposed seasonal freshet volumes have been determined by applying the seasonal distribution based on historical Colorado River freshet statistics (see Section 5.2). The results of applying this seasonal distribution are summarized in Table 23. The intent of these seasonal overlays is to create a comprehensive three-part criterion that embraces the variability and flow pulse requirements suggested by the bio-statistical work on abundance relationship to freshets, while maintaining average flow in the intervening months to stay nominally within the salinity ranges necessary to meet the habitat conditions consistent with the individual criteria. To meet a given criteria, each of the three flow component objectives would need to be satisfied in any given year, subject to the modified application of the MBHE 4 achievement guideline discussed above.

Table 23. Recommended MBHE inflow regime criteria and proposed distribution. All inflow values are applied at the Colorado River main stem above the GIWW.

Onset Month	Flow Distribution (% of annual)	INFLOW CRITERIA (Acre-feet)			
		MBHE 1	MBHE 2	MBHE 3	MBHE 4
Spring January February March April May	38%	114,000 ac-ft 3 consecutive month total	168,700 ac-ft 3 consecutive month total	246,200 ac-ft 3 consecutive month total	433,200 ac-ft 3 consecutive month total
Fall August September October	27%	81,000 ac-ft 3 consecutive month total	119,900 ac-ft 3 consecutive month total	175,000 ac-ft 3 consecutive month total	307,800 ac-ft 3 consecutive month total
Intervening Six months	35%	105,000 ac-ft Total for 6 month period	155,400 ac-ft Total for 6 month period	226,800 ac-ft Total for 6 month period	399,000 ac-ft Total for 6 month period
Achievement Guideline		90%	75%	60%	35%* (See Sec. 5.2)

***modified application as discussed in Section 5.2.**

While the regression models developed in the biostatistics analyses were not found suitable to determine independent inflow criteria, the bio-statistical data analysis can be employed to further confirm the adequacy of the flow values determined from the habitat work. Figures 43 and 44 show the white shrimp abundance versus fall freshet volume, and the Atlantic croaker abundance vs. the spring freshet volume. Note that in both the white shrimp and the Atlantic croaker data, MBHE 1-3 inflow criteria fall in a cluster of data points (shaded blue box) at the lower end of the flow spectrum. The threshold and MBHE 4 criteria essentially bound the cluster. The abundance measurements are highly variable at these flow levels, ranging over a factor of four to seven times the minimum recorded abundance measurement. This suggests that these flow criteria should provide abundance characteristics that have been routinely experienced in Matagorda Bay.

This is further supported by a separate analysis of the probability that a given level of abundance will be met (i.e., equaled or exceeded), given that the criterion level of flow is met. These probabilities for the white shrimp abundance regressed against fall freshet flow and Atlantic croaker abundance regressed against spring freshet flow are summarized in Tables 24 and 25.

While these tables present a range of abundance values, perhaps the abundance level of more interest is the historical minimal abundance (i.e., the lowest data point in Figures 43 and 44). These lowest values and the corresponding probabilities of exceedance for white shrimp and Atlantic croaker are shown in Table 26. MBHE 3 conditions would ensure that this minimal abundance is exceeded at least 95% of the time for both organisms, and even at the very low level of Threshold, a 90% exceedance is achieved.

It should be noted that the MBHE biostatistics analysis developed regression relationships based on that portion of the Colorado River flow which enters Matagorda Bay, whereas the inflow criteria are specified based on flow in the lower river. At the range of 3-month seasonal flow values specified in the inflow criteria, it is estimated that approximately 80% of the Colorado flow reaches Matagorda Bay, with the remainder going to East Matagorda Bay and the Gulf of Mexico. Hence, the flow values in Figures 43 and 44 and Tables 24 and 25 corresponding to the various inflow criteria values are adjusted accordingly.

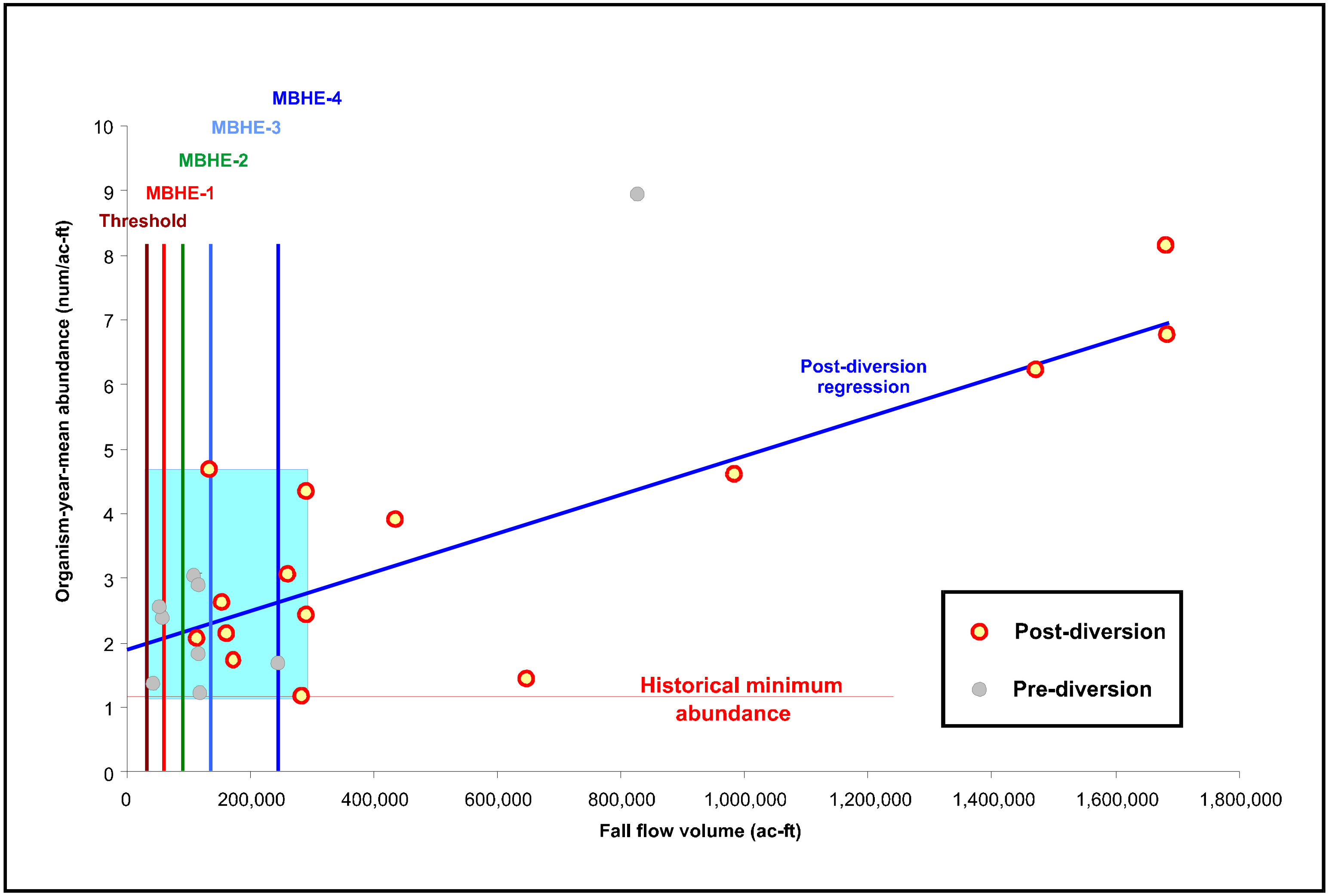


Figure 43. Whole bay otter trawl white shrimp abundance vs. flow - Colorado Flow to Matagorda Bay (COLMB) fall freshet (3Sub).

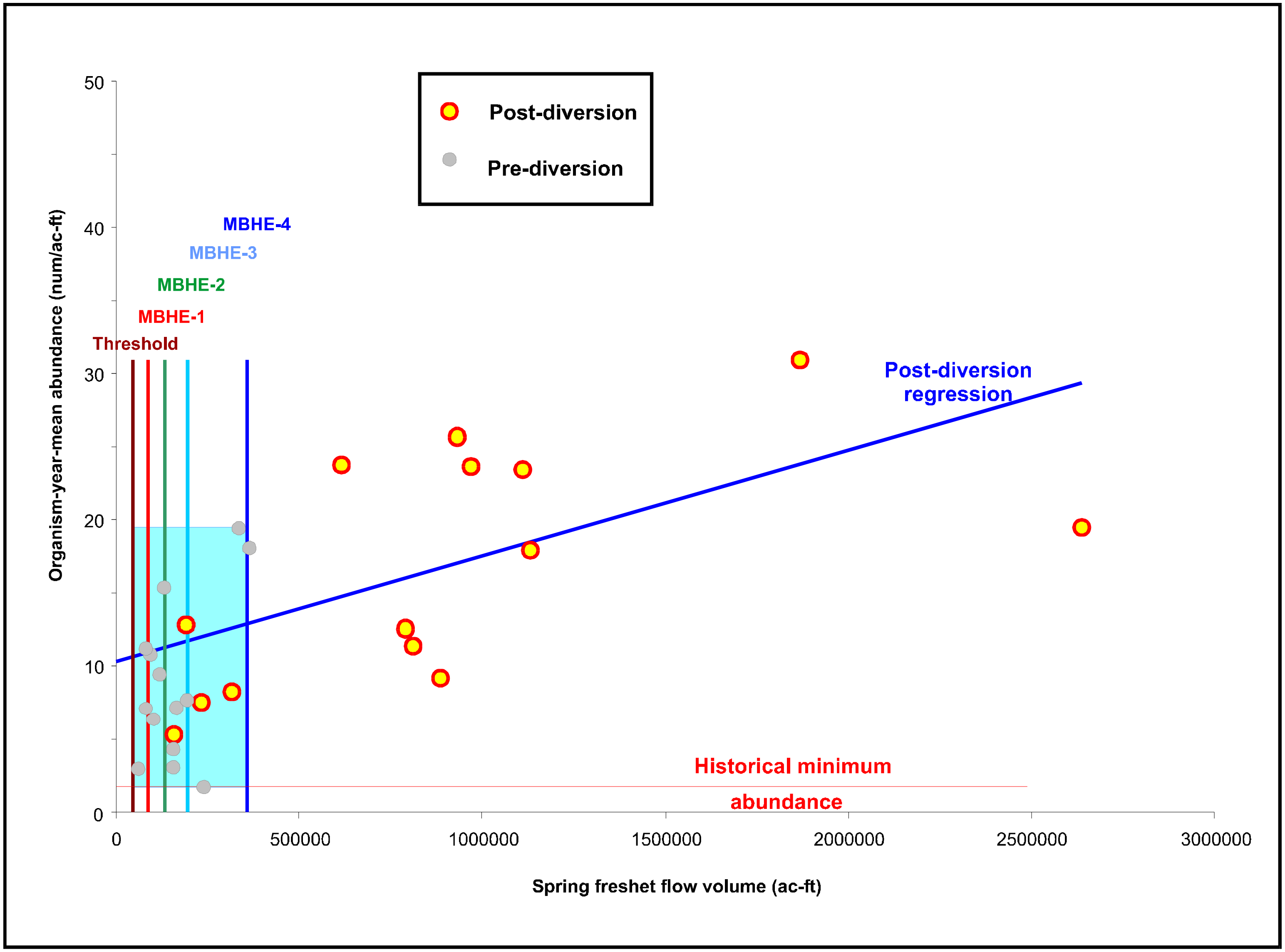


Figure 44. Whole bay otter trawl Atlantic croaker abundance vs. flow - Colorado Flow to Matagorda Bay (COLMB) spring freshet (3Sub).

Table 24. Probability (cumulative frequency) of white shrimp abundance exceedance given that the fall freshet equals or exceeds criterion values

		Inflow Criteria				
Abundance (no/ac-ft)		Threshold	MBHE-1	MBHE-2	MBHE-3	MBHE-4
	flows (ac-ft/3 mo)	34622	62431	92877	136866	247169
0.0		98.1	98.4	98.7	99.2	99.7
0.2		97.5	97.8	98.3	99.0	99.5
0.4		96.6	97.0	97.7	98.6	99.3
0.6		95.4	96.0	96.8	98.1	99.1
0.8		94.0	94.7	95.8	97.4	98.8
1.0		92.2	93.1	94.5	96.5	98.3
1.2		90.0	91.1	92.8	95.4	97.8
1.4		87.3	88.7	90.8	94.1	97.1
1.6		84.3	85.8	88.4	92.4	96.2
1.8		80.7	82.5	85.6	90.4	95.1
2.0		76.8	78.8	82.4	88.2	93.7
2.2					85.6	92.2
2.4						90.4
2.6						88.4
2.8						

Table 25. Probability (cumulative frequency) of Atlantic croaker abundance exceedance given that the spring freshet equals or exceeds criterion values

		Inflow Criteria				
Abundance (no/ac-ft)		Threshold	MBHE-1	MBHE-2	MBHE-3	MBHE-4
	flows (ac-ft/3 mo)	34622	88241	131830	195324	356464
0		97.7	98.0	98.4	98.8	99.3
1		97.0	97.4	97.9	98.5	99.0
2		96.0	96.6	97.3	98.0	98.7
3		94.9	95.5	96.4	97.3	98.3
4		93.4	94.2	95.3	96.5	97.7
5		91.6	92.6	94.0	95.5	97.0
6		89.4	90.7	92.4	94.2	96.2
7		86.8	88.3	90.4	92.7	95.1
8		83.7	85.6	88.1	90.8	93.8
9		80.2	82.4	85.3	88.7	92.2
10		76.3	78.8	82.3	86.2	90.3
11				78.8	83.3	88.2
12						85.8
13						

Table 26. Probability of organism abundance exceeding historical minimum given that the criterion freshet flow is met.

	Minimum abundance	year	Exceedance Frequencies (%)					
			Threshold	MBHE-1	MBHE-2	MBHE-3	MBHE-4	Controlling Freshet
white shrimp	1.17	2000	90.3	91.4	93.1	95.6	97.9	fall
Atlantic croaker	1.82	1980	96.2	96.7	97.4	98.1	98.8	spring

A final confirmation of the proposed criteria comes from an analysis of model results from the chlorophyll-*a* modeling reported in MBHE 2007c. On Figure 45, the model monthly average chlorophyll-*a* concentrations are plotted against the monthly EAMB inflows for the period 1995 to 2002 (the nutrient model's calibration period). The model shows the general relation of chlorophyll-*a* to inflow. There are a few months with average chlorophyll-*a* concentrations below 2 μg/L but relatively high inflow (>1,000 cfs), but the general pattern is what would be expected in a nitrogen-limited system. The inflows of the other months with concentrations < 2 μg/L are all below 600 cfs (36,000 ac-ft per month) and average 360 cfs (21,700 ac-ft per month). In effect, the model indicates that average monthly flows of about 22,000 ac-ft per month can support chlorophyll-*a* levels near the 95th percentile of existing data. Therefore, the MBHE 1 intervening month flow magnitude should be sufficient to maintain minimum primary productivity. Modeling also indicated that the MBHE 2 and MBHE 3 flows produces chlorophyll-a levels at the 7th and 11th percentiles of the historical (Post-diversion) data, while the MBHE 3 flows produce levels at the 26th percentile. These are reasonably close to the flow achievement guidelines so if the long-term average criterion is achieved, these inflow criteria values will be protective.

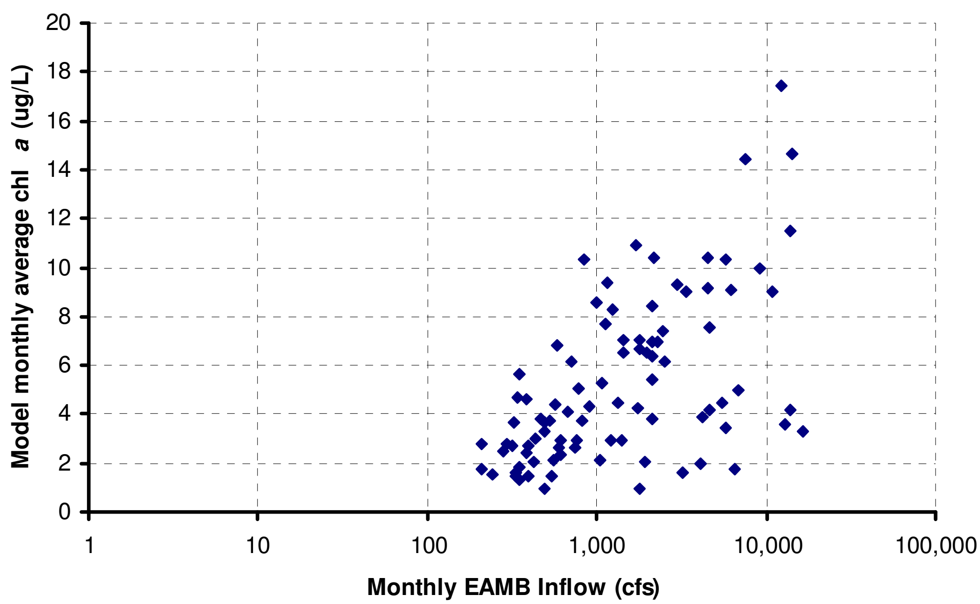


Figure 45. Relationship between model chlorophyll-a concentration and EAMB inflow.

5.3.3 Threshold Criteria

As discussed in Section 3.2, Threshold criteria include both a minimum flow and potential for pulse flows. Based on the salinity model results, the minimum flow necessary to maintain 30 ppt or less throughout the majority of the Colorado River Delta is approximately 15,000 ac-ft per month. This volume is predicted to have salinities ranging from 31 ppt at the Delta edge transect to just over 32 ppt at the Mad Island transect. Multiplying 15,000 acre-feet by 12 months results in an annual volume of 180,000 acre-feet. To maintain the refuge conditions sought by this criterion, a fixed monthly distribution is recommended rather than a seasonal distribution, with the proviso that active management might suggest circumstances in which scheduled flows could be accumulated to provide the ability to create a larger pulse of flow.

In addition to the Threshold monthly inflow requirement, it is anticipated that extended drought conditions might require additional measures to protect oyster health and provide refuge for key species within the Colorado River Delta. It is recommended that a real-time monitoring program be established for salinity and temperature within the Delta along with routine biological monitoring. Additionally, low-inflow triggered biological sampling (including dermo monitoring) is also suggested. With this monitoring approach, actual field data from the Delta could be used to determine if and when flow distribution or timing may need adjustment in order to enhance protection of oysters and refuge habitat. Monitoring data could also be used to refine the DCI statistical relationship and strengthen the habitat and benthic models allowing more confidence in the predictive capabilities of those tools.

In summary, Threshold criteria promote a tiered approach to assist in protecting the character of Matagorda Bay. The first is by ensuring a minimum inflow aimed at sustaining the benthic character and providing habitat refuge for juvenile organisms. These fixed releases also buy time in supporting tolerable conditions for oysters to the degree practical under extremely low flow conditions. The second tier involves active monitoring and cooperative management that could potentially inform and guide changes in the distribution and/or timing of Threshold inflows to better support ecological conditions within the Delta.

5.4 WAM Implementation

The suite of proposed inflow criteria:

- cover the full spectrum of flow conditions experienced in the Colorado River, which are related to certain bay condition results;
- incorporate guidelines for the frequency of occurrence of the various condition levels; and
- reflect the benefits which accrue to flow pulses in the Spring and Fall months.

The remaining step is to develop an implementation strategy for meeting the proposed criteria. The principal difficulty in this implementation step is the fact that the achievement guidelines for all of the various criteria levels are intended to be long-term frequencies of occurrence. The long-term flow category is expressed as a long-term average and variability and is to be maintained. Also, the goal is that inflow does not fall below the minimum Threshold inflow levels. The MBHE inflow regime criteria all have recommended guidelines for their respective occurrence frequencies. All require passage of time to assess success or failure.

The WAM model provides a method to assess on a projected basis the likelihood that the suite of inflow criteria will be met and also a tool by which system operating protocol can be established which will yield the desired inflow results. The WAM for the lower Colorado River, as modified by the LSWP Surface Water Availability team, incorporates a 59-year historical hydrology period (1940 – 1998), and, using a calendar monthly timestep, can simulate future demand scenarios both with and without the LSWP.

The resulting projected inflow into Matagorda Bay of any such simulation can readily be post-processed to determine if the full suite of inflow criteria are achieved at the desired frequencies. If not, then the system operating rules, including when releases from storage are required, can be modified, continuing in an iterative process to determine whether and under what operational rules the full suite of criteria may be expected to be satisfied. Once sufficient operating protocol are established that satisfy the full suite of inflow criteria, the presumption is that adherence to these operating constraints will likely result in long-term satisfaction of the inflow criteria. Finally, the WAM can be re-run at any time that significant changes in input conditions become apparent.

Further processing of the WAM projections of bay inflow can address the concern of extending the duration of low flow periods, and if apparent, further adjustments can be made to the operating protocol. Finally, as the WAM model is still a projection based on the assumption that historical hydrology will be repeated, nothing can fully replace the need for continued monitoring of the bay system, using the new information and data to validate and update the modeling tools employed in the MBHE on a regular basis.

6.0 Relationship of MBHE Inflow Criteria and FINS

The MBHE team recognizes the extensive work done by LCRA in conjunction with state resource agencies in assessing freshwater inflow needs for Matagorda Bay. In August of 2006, LCRA, in conjunction with several state agencies, published the results of a study whose purpose it was to reassess the freshwater inflow needs of Matagorda Bay. The study is generally referred to as the 2006 FINS and was undertaken through a cooperative agreement with TPWD, TWDB and TCEQ. The 2006 FINS was an update of an earlier freshwater inflow needs assessment completed in 1997, and its primary purpose was to

- better understand the relationship between flow volume and seasonal timing and Matagorda Bay "environmental conditions", and
- better estimate freshwater inflow needs necessary to "maintain and preserve the bay's aquatic ecology".

The FINS report (FINS 2006) makes it very clear that it is not intended to determine how the various study participants would implement any of the findings, but acknowledged that there were several ways in which the results might be employed.

6.1 Overview of Objectives and Methodology

In order to discuss the similarities and differences between 2006 FINS and MBHE, it is helpful to establish how a few terms will be used to facilitate the comparison. The first of these is an environmental **objective** to be met in the bay. Often, various **measures** are employed to characterize aspects of the bay environment. In order to achieve a certain objective which is related at least in part to volume and timing of freshwater inflow, **inflow criteria** can be developed that if satisfied, should yield the desired objective. Finally, having developed the inflow criteria, system **operating protocol** can be established that, if followed, are projected to achieve both the magnitude and desired frequency of occurrence of the inflow criteria. In essence, operating protocol lead to inflow criteria being met which should produce the desired objective in the bay. This particular terminology is not the only alternative, but it does seem to adequately describe the necessary cause and effect relationships which are fundamental to both FINS and the MBHE studies. Both use various terms which can be characterized using the above terminology. Objectives in the bay are referred to in:

FINS - generally as maintaining and preserving the bay's aquatic ecology. More specifically, FINS defines certain productivity objectives related to a collection of important species, and providing refuge areas under low flow conditions. In the later case, an actual numerical objective for salinity is established as the measure of bay condition. In all cases, general and specific, these can be considered objectives based on specific measures.

MBHE - overall as maintaining bay health and productivity. Through the use of several models developed during the studies, this overarching objective is substantially refined by establishing certain numerical objectives for maintaining measures, including salinity, habitat and benthic conditions, and nutrient loading deemed conducive to maintenance of bay health.

The methodologies used in the two studies to develop inflow criteria differ substantially. Table 27 provides an overview of the objectives and study methodology. Both the 1997 and the 2006 FINS recognized that there are several important factors that relate to and should influence the establishment of bay inflow needs, but are currently not addressed by FINS. These include

- Nutrients (both loading and as related to primary productivity),
- Benthic dynamics,
- Sedimentation, and
- Existing habitat conditions

In FINS (2006), reference is made to the ongoing MBHE studies and its intention to incorporate, insofar as possible, these additional drivers of bay health in its analyses.

The final result of FINS is in fact inflow criteria, referred to in the study as "inflow needs". Similarly, MBHE has developed a set of inflow needs (presented herein) that are projected to result in the maintenance of bay health and productivity. Both studies acknowledge, while not the only driver of bay condition, freshwater inflow is the primary mechanism over which some level of control can be effected.

Table 27. Overview of Criteria Objectives and Methodology.

Inflow Category	FINS (2006)	MBHE
Long-Term	**Not applicable.** FINS does not establish a long-term flow criteria calling for a specific long-term average annual flow volume to be achieved, nor does it establish a measure of variability in annual flows to be maintained.	**Long-term Volume and Variability** – to be maintained along with a specific coefficient of variation in flow over the long term. The developed long-term flow volume and variability were based on maintaining nutrient loading sufficient to achieve the historical level of primary productivity in the bay. Hydrodynamic modeling coupled with WASP nutrient modeling were employed to develop these recommendations.
Inflow Spectrum	**TARGET - FINS** applied the State Methodology, with specific constraints, to determine the flow necessary to optimize the productivity of a suite of key species. This recommendation does not "optimize" bay productivity as key species have different optimal requirements; rather, the optimization program incorporates all species into a balanced solution. The results recommend a set of monthly flow targets for the Colorado River. No guidance is provided on how frequently this condition should be achieved. **CRITICAL - FINS** yielded a Critical monthly inflow criteria based on maintaining an average salinity at the West Bay Tripod location with the underlying objective to provide suitable conditions for oysters and refuge for other species. No specific methodology for developing the linkage of salinity to suitable conditions was defined. No guidance was provided on how frequently this condition should be achieved.	**MBHE Inflow Regime** - The focus of the MBHE freshwater inflow criteria development is on a trophic level assessment that evaluates primary productivity, marsh productivity, the health/condition of oyster reefs, the available habitat for juvenile shellfish and forage fish, and the maintenance of benthic conditions in Matagorda Bay over a range of conditions which Matagorda Bay has historically observed. **MBHE 4** - provide inflow variability and support high levels of primarily productivity, and high quality oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat. **MBHE 3** - provide inflow variability and support quality oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat. **MBHE 2** - provide inflow variability and sustain oyster reef health, benthic condition, low estuarine marsh, and shellfish and forage fish habitat. **MBHE 1** - maintain tolerable oyster reef health, benthic character, and habitat conditions. These criteria call for Spring and Fall seasonal pulses plus additional flow in the intervening months. The recommended criteria are accompanied by achievement guidelines and they are intended to be applied simultaneously. Specific models (juvenile forage fish and shellfish habitat, oyster condition, benthic condition, and marsh productivity) were constructed, and in many instances linked to hydrodynamic/salinity modeling.*
Minimum	**Not applicable.** FINS did not propose any maintenance of minimum flows under all conditions, using stored water as necessary.	**Threshold** - criteria that is based on providing refuge conditions for oysters, shrimp, crab, and fish habitat within the Delta. A specific inflow is specified for all months, with the goal not to fall below the threshold level by using storage as necessary.

*The MBHE studies did encompass extensive analysis of both linear and non-linear relationships between inflow and species abundance using the same TPWD data base utilized in the State Methodology. Relationships of inflow to abundance from these analyses were determined and in some cases, were quite strong. However, the lack of data and scatter around the data did not lend this analysis to be converted to inflow criteria. Rather, the MBHE biostatistical analysis was used to support and confirm criteria developed using other MBHE models.

6.2 Comparison of Inflow Criteria

As highlighted in Table 27, the specific inflow criteria recommendations to meet FINS objectives are referred to as Target and Critical, respectively. In addition, FINS (2006) recognized that much of the time, hydrologic conditions are neither at the Target or Critical flow levels; hence there is need for management of flows during the frequently occurring intermediate hydrological conditions. The study did not offer specific recommendations for intermediate inflow criteria, but rather suggested some techniques by which the underlying FINS models and methods might be employed to determine appropriate intermediate flow criteria. It is noteworthy that, while FINS (2006) made no specific recommendations other than Target and Critical criteria, LCRA has proposed an inflow criteria of 1.5 times the Critical FINS as an intermediate value in its pending water management plan (WMP) revisions. As the intent of this section is to compare FINS to MBHE, the LCRA intermediate flow criteria is not carried forward in the discussion.

The 2006 FINS recommended Target inflow criteria for the Colorado River is 1,428,000 AF per year, distributed monthly, as summarized in Table 28 (FINS Target monthly recommendations on Table 7.3 of the 2006 FINS report.). This volume represents the Colorado River contribution to bay-wide Target inflow criteria of 2.75 million AF per year determined by applying the State Methodology with selected constraints. The recommended FINS Critical inflow criteria is 36,000 AF per month from the Colorado River, which is based on maintaining a 25 ppt salinity (on average) at the West Bay Tripod location. The MBHE freshwater inflow criteria as discussed throughout this report are also summarized in Table 28.

While the overall objective of FINS and MBHE studies are similar in nature, there are important differences that make direct comparison of the results less than straightforward. The MBHE studies are focused on projecting bay health and productivity into the future so as to allow assessment of the impacts of implementing the LSWP and to ascertain if the legislative mandates are satisfied. In doing so, the study team has been directed to utilize the best available science. While not specifically requiring the development of inflow criteria, the utility of doing so is clear. A bridge between bay condition and operating protocol is necessary, and inflow criteria provide a method of linking the two. FINS is predicated first on the State Methodology, which seeks to determine an inflow pattern needed to optimize the productivity of the Matagorda Bay complex. It is not geared to assessing future bay health conditions based on projected system demands. Correspondingly, there is no analyses within the MBHE that attempts to optimize bay productivity. The methodology employed in the FINS as it was extended beyond the State Methodology to determine Critical inflow criteria is more similar in nature to the MBHE studies, and both studies recognize that something above extreme low flow criteria, but much less than flood flows, is also an important element that should be addressed.

Table 28. Comparison of numerical criteria and achievement guidelines.

Inflow Criteria	FINS (2006)	MBHE	ACHIEVEMENT GUIDELINE
Long-term Volume and Variability		1.4 to 1.5 Million Acre Feet (MAF) per year, Coefficient of Variation should exceed 0.8.	100% - Based on Water Availability Modeling (WAM) results.
FINS Target	Monthly flow targets for the Colorado River ranging from 60,400 AF in April to a high of 255,400 in May. The sum of the individual monthly targets is 1,427,800 AF for the year.		Based on Lake levels and inflow to the Highland Lakes. No set percentage to be achieved is specified.
MBHE 4		Spring and Fall seasonal pulses plus additional flow in the intervening months. Based on monthly average flows of 95,000 acre-feet. The sum of seasonal flows is 1,140,000 AF for the year.	35% - Based on Water Availability Modeling (WAM) results (see discussion in Section 5.2).
MBHE 3		Spring and Fall seasonal pulses plus additional flow in the intervening months. Based on monthly average flows of 54,000 acre-feet.	60% - Operating protocol "triggers" are to be established to manage flows by releases from storage so as to satisfy.
MBHE 2		Spring and Fall seasonal pulses plus additional flow in the intervening months. Based on monthly average flows of 37,000 acre-feet.	75% - Operating protocol "triggers" are to be established to manage flows by releases from storage so as to satisfy.
FINS Critical	Monthly inflow criteria of 36,000 AF per month		Based on Lake levels and inflow to the Highland Lakes. No set percentage to be achieved is specified.
MBHE 1		Spring and Fall seasonal pulses plus additional flow in the intervening months. Based on monthly average flows of 25,000 acre-feet.	90% - Operating protocol "triggers" are to be established to manage flows by releases from storage so as to satisfy.
Threshold		Monthly inflow criteria of 15,000 AF per month	100% - Use storage as necessary.

As noted earlier, FINS Critical is predicated on meeting a specific salinity objective at the West Bay Tripod location. Furthermore, the recommendation suggests meeting this level on average, and the long-term model simulation in the FINS report projects that the 25 ppt level would be exceeded 32% of the time, which is likely underestimated given the tendency for the TXBLEND model to under predict salinity at the Tripod location. Salinity also plays an important role in the MBHE inflow criteria. Habitat conditions suitable for juvenile species at several trophic levels have been related to ranges of salinity throughout the Design Area and within the Delta. Similar to FINS, these ranges of salinity were related to inflow through the use of both model and data analyses at several points in EAMB. However, rather than depending on a single salinity value at a fixed location, which was then related to a single monthly flow value, the MBHE approach entailed a broader geographic area and multiple ranges of salinity as they related to habitat conditions. This led to the development of inflow regime criteria (MBHE 1-4) with accompanying achievement guidelines which increase as drier conditions are experienced. It is suggested that all MBHE inflow regime criteria levels apply simultaneously, including providing at all times the minimum monthly flows included in the Threshold criteria. In contrast, FINS does not ensure a minimum flow to the bay.

There are two additional attributes to the MBHE suite of criteria that are absent from FINS Critical. The four MBHE inflow regime criteria (MBHE 1-4) embrace an element of variability which reflects more realistic naturally occurring conditions. For each, seasonal variability is accommodated which better reflects the reality that seasonal flow pulses in the Spring and Fall do not follow a fixed monthly calendar from year to year, and the bay species are adapted to that variability. Also, the recommended Threshold criteria go beyond a simple set of minimum monthly flows. As discussed in Section 5.3.3, it is envisioned that a second tier will be developed for threshold criteria in conjunction with stakeholders. This step involves active monitoring and cooperative management that could potentially inform and guide changes in the distribution and/or timing of threshold inflows to better support ecological conditions within the Delta.

In summary, incorporation of the multiple measures (including most of the components identified as important but not currently addressed by FINS) of bay health in the MBHE inflow regime, coupled with a guaranteed minimum inflow and long-term average flow volume and variability, enhanced with specific attainment guidelines, would appear to result in a more comprehensive approach to inflow criteria than offered by FINS.

7.0 Other Key Issues

7.1 Integration with Colorado River Instream Flow Guidelines

As the Colorado River is a major contributor of inflow to Matagorda Bay, integration of the MBHE Freshwater Inflow Criteria with the Instream Flow guidelines (BIO-WEST 2008) for the river is important and appropriate. Two areas stand out where integration is essential:

1) The first is the coordination of river high flow pulse events within the context of the MBHE freshet approach. The majority of the high flow pulses and all overbanking flows (characterized in the River study) that will contribute to the larger freshet events cannot be controlled. However, smaller scale mandatory flood releases that might allow management options for river release could be coordinated with the MBHE freshet goals.
2) Secondly, potential adjustments in the timing of Threshold inflow releases should be coordinated with the lower tier flow pulses discussed in the Colorado River instream flow guidelines. During periods of limited water availability, this coordination would allow those pulses to maximize the benefit to both the riverine and bay environment.

7.2 Long-term Monitoring

Long-term monitoring of the conditions in Matagorda Bay will provide the ultimate measure of the effects of any change to which the bay system is subjected. Like other Gulf Coast estuaries, the Matagorda Bay system is a highly dynamic environment that reacts to many drivers including freshwater inflow. Thus, the establishment of a long-term monitoring program for Matagorda Bay is an integral element of the MBHE freshwater inflow criteria. The recommended monitoring program is inherently designed to assess the effectiveness of the MBHE inflow criteria over time, and to provide useful information about trends and changes in bay condition and their causes. To properly guide the development of a long-term monitoring program, and avoid the trap of monitoring for the sake of monitoring, the fundamental question to be addressed is:

- What information would readily improve confidence in refinement and utilization of the MBHE assessment tools, to better address the question of potential impacts and/or the refinement of freshwater inflow criteria?

The development of baseline conditions is essential. In some cases, this will most efficiently be accomplished by including, refining, or expanding upon existing monitoring programs (e.g. LCRA, state agencies, DermoWatch, etc.) that are already established in Matagorda Bay. During the MBHE study period, several data collection efforts were conducted to assist with model development, validation, and data analysis. These efforts provide the foundation for long-term monitoring activities. To a lesser extent, additional data collection activities that were specifically acknowledged as being data limitations during the MBHE are proposed to expand the knowledge base available for the Matagorda Bay system. Finally, the monitoring program has been developed with an adaptive framework, which will allow for the review and assessment of the data collection activities as well as refinement of the monitoring plan into the future.

The recommended MBHE long-term monitoring program involves assessment across the entire Matagorda Bay system, with particular emphasis on the Colorado River Delta, EAMB, select marshes north of the GIWW, and East Matagorda Bay (EMB) since these areas have the greatest potential to be affected by changes in Colorado River flow and changes in agricultural practices. The long-term monitoring program follows the framework established and used throughout the MBHE by focusing on the key measures that were selected to characterize bay health and productivity:

- salinity;
- habitat;
- abundance;
- bay food; and
- benthic condition.

As described in previous MBHE documentation, each measure supports several components. For instance, the habitat assessment involves marsh community structure, marsh productivity, oyster reef condition, and habitat (defined as the combination of physical and chemical habitat) for juvenile shellfish and forage fish. Concurrently, there is significant interdependence between the various measures of bay health that are being addressed by the MBHE studies and the recommended long-term monitoring program. In many cases, these interdependencies are linked by freshwater inflow and salinity conditions. A key component already identified in this document is the need for long-term salinity and temperature data collection within the Colorado River Delta and near oyster reefs in EAMB. Additionally, biological data collection in areas traditionally not sampled by the resource agencies (in the Delta and the marshes) will be critical to improving the understanding of the ecological dynamics of these areas and allow for adaptive management decisions in the future.

The recommended monitoring program will employ control sites (either through direct sampling or data analysis of existing monitoring programs) in an attempt to help identify the cause of measured change, and to identify potential inflow criteria deficiencies. An example of control sites to be tested via direct sampling is the benthic long-term monitoring. Six benthic monitoring stations are proposed to characterize change within the study area. These stations include building upon the three long-term stations in Matagorda Bay by adding three additional sites: a site in the Delta area, a site in EAMB (between Station E and F, Figure 16), and a permanent site in EMB. The three existing long-term stations in Lavaca Bay will be maintained as reference stations. These reference sites are included as a control point to identify changes at a larger spatial scale. Prime examples of using data collected by established programs are periodic evaluations of TPWD coastal fisheries data and DermoWatch data from throughout the bay system. The random nature of the TPWD dataset and structured format of the DermoWatch program provide two differing levels of reference testing for components of the MBHE biological sampling.

The MBHE team is completing the development of the recommended long-term monitoring program in coordination with LCRA and SAWS resource professionals and program staff ,within the context of discussions and suggestions provided by the independent Science Review Panel, resource agencies, environmental organizations, and others during stakeholder involvement over the past four years. The formal document will be prepared under separate cover at which time additional input will be solicited via the LSWP stakeholder process. All or part of the program may be implemented by various entities subject to funding availability.

7.3 Adaptive Management Overview

As stated throughout the LSWP, there are uncertainties surrounding many components of the project including freshwater inflow criteria, instream flow criteria, agricultural conservation strategies, etc., and how these components will function in the context of future flows in the river and local watershed. Therefore, it is acknowledged that a flexible adaptive management plan should be prepared by the LSWP program team. As discussed in Section 1, the MBHE recommended long-term monitoring plan is one component that can be incorporated into that overall adaptive management effort. The MBHE long-term monitoring plan is designed to provide information about trends and changes in bay conditions and their causes, assess the effectiveness of the MBHE inflow criteria, and to improve the understanding of the ecological dynamics of Matagorda Bay. Thus, when implemented, the monitoring program will provide key information about bay conditions, which, when analyzed, will provide input to an adaptive management of inflow and other manageable drivers of bay health.

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